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Restoring Floodplains in the Connecticut River Basin: A Flood Management Strategy

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RESTORING FLOODPLAINS IN THE CONNECTICUT RIVER BASIN: A FLOOD MANAGEMENT STRATEGY

A Masters Project Presented

by

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Abstract Page

This research investigates how changes to floodplains in the Connecticut River Basin impact flood events. Climate impacted flows and increased development within the floodplain could lead to worsening flood events and less habitat availability for threatened species. Potential future conditions are evaluated through a wide range of scenarios to assess the range of possible impacts using a HEC-RAS 2D model. Three different flood events, 1-yr, 10-yr, and 100-yr, are evaluated for each scenario. Five metrics, Discharge, Depth, Time of Arrival, Flooding Duration, and Number of Buildings Flooded, are tracked for each scenario. These metrics are compared to select the ideal course of action given multiple potential objectives. For interested organizations, environment and human impact often have contradictory goals that decision makers must try to balance. The results of this analysis provide crucial information to help inform these decision makers. As floodplain restoration efforts increase, flood peaks decrease and habitat suitability improves. Restoration leads to reduced flood risk for downstream inhabitants, however, the number of impacted people residing in the floodplain increases. Flood duration also increases expanding the available suitable land for restoration focused efforts. Alternatively, as development in the floodplain grows, flood events increase flood risk for downstream inhabitants, while habitat suitability diminishes and the impact to floodplain residents decreases.

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1.0 Problem Statement

One of the more nuanced issues regarding our water resources future is how changes in floodplains will impact flood events. This complex issue introduces uncertainty for flood events and how best to prepare and manage for these events. Flood events are impacted by precipitation (intensity, duration, amount, timing, and phase) and drainage basin conditions (water level in river, snow pack, soil characteristics, land use/land cover [LULC], and existing structures such as dams and reservoirs) (Bates, Kundzewicz, Wu, & Palutikof, 2008). Increased development within floodplains is often a consequence of population growth. Changes in the LULC due to development can impact flood events in unexpected ways. With climate change, precipitation events are projected to become more intense, increasing the frequency, extent, and impacts of flooding (Bates, Kundzewicz, Wu, & Palutikof, 2008; Jonkman, 2005; Tetra Tech, 2013; Emanuel, 2013; Kunkle, et al., 2013).

Quantifying the impact of changes in land use and climate on extreme hydrologic events is particularly challenging. There lacks agreement in the projections of changes in fluvial floods due to limited consistent evidence and the complexities of regional changes (Seneviratne, et al., 2012). Research suggests that an increase of 10-30% in flood discharge could result in a 100-year flood event today occurring every 10-50 years in the late century (Hirabayashi, et al., 2013).

Flooding is the most frequent natural disaster to occur and impacts people worldwide, affecting over 1.4 billion people in the 20th century (Jonkman, Global Perspectives on Loss of Human Life Caused by Floods, 2005). Throughout history, humans have settled near rivers and in floodplains as they offer access to freshwater, fertile lands, and predefined travel routes (L.R. Johnston Associates, 1992; Tetra Tech, 2013; Plate, 2002; Freitag, Bolton, Westerlund, & Clark, 2012; Dawnson, et al., 2011). Increasing population has led to increased fragmentation of freeflowing rivers and their associated floodplains, caused by the construction of levees, dams and other infrastructure. Some of the negative impacts associated with this infrastructure include temporal and spatial river flow redistribution, river flow withdrawal, physical disturbance of riverbeds, pollution, water clogging, thermal pollution, and migrating species mortality and delay (Govorusho, 2007; Tetra Tech, 2013; Freitag, Bolton, Westerlund, & Clark, 2012).

Flood risk management allows use of rivers through the management and the planning of systems to reduce flood risk (Plate, 2002). Flood risk is the combination of the probability of an event occurring and the impacts of the event if it occurred. Traditional flood risk management involves the use of structural approaches to control and impact discharge. However, research suggests that the combination of structural and non-structural methods of flood control can more effectively mitigate flood risk (Faisal, Kabir, & Nishat, 1999; Hall, Meadowcroft, Sayers, & Bramley, 2003; Dawnson, et al., 2011).

This research explores how protection and restoration of floodplains can be used as part of a flood management strategy, with the added benefit of promoting ecological health. Portions of the Connecticut River Basin are used as a case study. This research quantifies potential changes in key parameters such as the volumetric flow rate, the length of flooding, and the acres of land flooded. The research helps quantify and identify areas where ecological preservation and restoration can provide the most benefits to humans and floodplain ecosystems.

2.0 Background

2.1 Traditional Flood Management

Flood levees and flood control dams are the most common flood protection methods in the United States. River systems are negatively affected by structural methods of flood control in a multitude of ways including: the alteration of instream water temperatures, the reduction of naturalized flow, the transformation of river channels and floodplains, the disruption of sediment transport to the river system, increased challenges to species migration, and the fragmentation of river continuity (Akanbi, Lian, & Soong, 1999; Govorusho, 2007; Higgs, Maclin, & Bowman, 2002; Tetra Tech, 2013; Petts, 1984). Traditional flood control management has well-documented negative impacts that extend beyond just riverine and floodplain health (Govorusho, 2007; Akanbi, Lian, & Soong, 1999).

Levees "can be thought of as dams built roughly parallel to a stream rather than across its channel" (L.R. Johnston Associates, 1992, p. 37). Although levees are the most frequently implemented flood control structure, there are many risks and problems associated with their use. A significant percentage of levees are privately or locally built and are not regulated by a governmental agency such as the United States Army Corps of Engineers [USACE]. These levees provide limited protection during floods because many are poorly designed and maintained or because they were built with agricultural objectives instead of flood protection objectives (L.R. Johnston Associates, 1992). Levees often provide an unjustified sense of security for the local community, leading to additional development within the floodplain. Moreover, because many levees are built locally, they often do not consider other flood control structures along the river, including other levees. Levees isolate the river from its floodplain and the storage of water associated with a floodplain is then lost. The result is increased water elevations during floods as water is forced to remain in the river channel and downstream levees can be rendered ineffective (Akanbi, Lian, & Soong, 1999).

The construction of a levee also confines a river that once had a shifting river bed. This creates sediment deposits within the river bed, which can raise flood stages to higher levels (Plate, 2002). When levees fail, high velocities of water are concentrated in the area where failure occurred causing more damage than if no levee had existed, or a levee system can keep the water from leaving the formally protected area, thereby increasing the flooding duration (Freitag, Bolton, Westerlund, & Clark, 2012; L.R. Johnston Associates, 1992). Despite their widespread use, historically, levees have accounted for "approximately one-third of all flood disasters"; disasters that could be reduced with a more comprehensive suite of flood management tools (L.R. Johnston Associates, 1992, p. 37).

Flood control dams are effective in limiting the impacts of flooding, and are used throughout the US and the world. Proper operation of these reservoirs can reduce water velocity, change the timing of the peak flood flow, reduce the peak flood flow, and minimize the flooded areas (L.R. Johnston Associates, 1992). However, dams can be insufficient to prevent flood events for a variety of reasons. Many dams have multiple purposes in addition to flood-control, including hydropower production, recreation, water supply, and navigation. Research also suggests that large dams can change local climates, by generating more local moisture and they can increase the availability of electricity; both of which tend to attract additional development and increase land cover changes (Degu, et al., 2011; Hossain & Jeyachandran, 2009; Woldemichael, Hossain, Pielke Sr., & Beltrain-Przekurat, 2012). Furthermore, dams restrict water flow and often change sedimentation transport patterns leading to an increase in sedimentation in the reservoir (L.R. Johnston Associates, 1992).

Many local, regional, and federal government agencies alter stream channels, broadly described as channelization, to increase the efficiency that a river moves water downstream as a flood control practice. Channelization is a widespread practice that involves bank stabilization, clearing, straightening, widening, and deepening of the channels. Its use is often underrepresented due to how easy it is for private owners to perform many aspects of channelization without record (Mattingly, Herricks, & Johnston, 1993). Channelization is widely accepted as detrimental to riverine ecology and to downstream inhabitants as it increases river velocities.

High flow diversions are also structured flood control methods implemented in the United States. These diversions convey excess water out of the natural stream bed through a channel to reroute high flows around an area of interest. Like other structural solutions to managing extreme events, diversions are harmful to the ecology of the river and can provide a false sense of security to nearby inhabitants (L.R. Johnston Associates, 1992).

These major methods of flood control are routinely implemented throughout the United States, including the Northeast. However, as Plate reminds us, “no technical solution to flooding is absolutely safe. Even if the system always does what it is supposed to do” (2002, p. 3). This concept is reinforced through inspection of historic flood disasters that often had flood control structures which were in some way insufficient for the flood event (Freitag, Bolton, Westerlund, & Clark, 2012).

Furthermore, the frequency and intensity of storms with a return interval of 100 years or greater has increased significantly in the Northeast due to change in local climate (Melillo, Richmond, & Yohe, 2014). This change in storm patterns may make current structures insufficient to deal with these high flows because future flood flows may be greater as compared to those in the past (Tetra Tech, 2013). These factors highlight the possible shortfalls of a dam and the need for more robust complete flood management plans.

2.2 Alternative Flood Management Strategies

Despite the ubiquity of structural flood risk management methods, there are non-structural alternatives. These flood management alternates seldom involve alterations to the natural river. Some examples of non-structural methods are watershed management, regulations and laws alongside economic incentives and deterrents, better flood forecast systems, insurance, updated, broader flood risk assessments, and public education campaigns to improve awareness (Bogardi & Kundzewicz, 2002; Dawnson, et al., 2011; Faisal, Kabir, & Nishat, 1999; Hall, Meadowcroft, Sayers, & Bramley, 2003; Plate, 2002; UNISDR, 2009).

This research focuses on changes in the floodplain, which manifest as watershed management, regulations, and other motivators to limit development and allow for the flow regime patterns to change, which in turn protects downstream inhabitants from flood waters. The broad concept of watershed management encompasses management opportunities such as changes to LULC and soil conservation, with a basic goal of changing the flood event. The overall concept is to increase infiltration within the watershed, augment storage catchments, and reduce impermeable surfaces with the goal of increasing water retention (Faisal, Kabir, & Nishat, 1999; Kundzewicz, 2001). Regulations and laws can influence the development within a floodplain. For example, zoning laws can prevent further development within a floodplain (Dawnson, et al., 2011). More comprehensively defined flood zones can better identify "at risk" areas and prevent intensive development within the identified areas (Faisal, Kabir, & Nishat, 1999). Local, state, and federal government bodies, as well as NGOs, can acquire developed land that are at risk for flood damages. These lands can be protected or restored to natural floodplain forest, increasing both the resistance to flow and increasing the acres of floodplain allowed to flood. Watershed management reduces risk by increasing the time it takes water to move through a watershed.

Consideration of non-structural solutions to reducing flooding events provides the opportunity to maintain functioning floodplains. While non-structural methods are not typically sufficient to adequately address all flood risk needs, they can be utilized in conjunction with structural methods to create a more robust flood management system with the added benefit of improving floodplain ecosystems.

2.3 Benefits to Functional Floodplains

Functional floodplains are a critical and valuable ecosystem that provides a multitude of services including flood and erosion control, water quality maintenance, replenishment of groundwater, support for a variety of plants and animals and maintenance of harvests, locations for recreation, scientific study, and outdoor education, as well as being sites of historic and archeological significance (Di Baldassarre, 2012; Marks, Lutz, & Olivero Sheldon, 2011; Tetra Tech, 2013). Natural floodplains are a complex mixture of flora and fauna that increase the natural system's resiliency (Freitag, Bolton, Westerlund, & Clark, 2012). Floodplains allow the dispersal and temporary storage of flood waters (Figure 2.1). This storage reduces flood peaks and, in turn, protects the downstream inhabitants and developments (Tiner, 1985). Additionally, vegetation and woody debris in the floodplain reduces the water velocity. Lower energy waters cause less erosion and scour. Unimpacted floodplain soils also filter more water than a structured channelized system without a floodplain. This elevated level of infiltration helps to maintain and improve the integrity of the surface water and increases the storage of groundwater supplies (L.R. Johnston Associates, 1992; Freitag, Bolton, Westerlund, & Clark, 2012). The

FEMA identifies social benefits of floodplains, as: “provide opportunities for hiking, camping, hunting, fishing, boating, swimming, bird-watching, picnicking, jogging, photography, ice skating, nature observing, as well as for scientific study and research, educational activities, and less tangible aesthetic benefits. Floodplains can provide urban communities with a tremendous open-space and greenbelt resource. Inland floodplains are great sources of commercial timber” (L.R. Johnston Associates, 1992, p. 12).

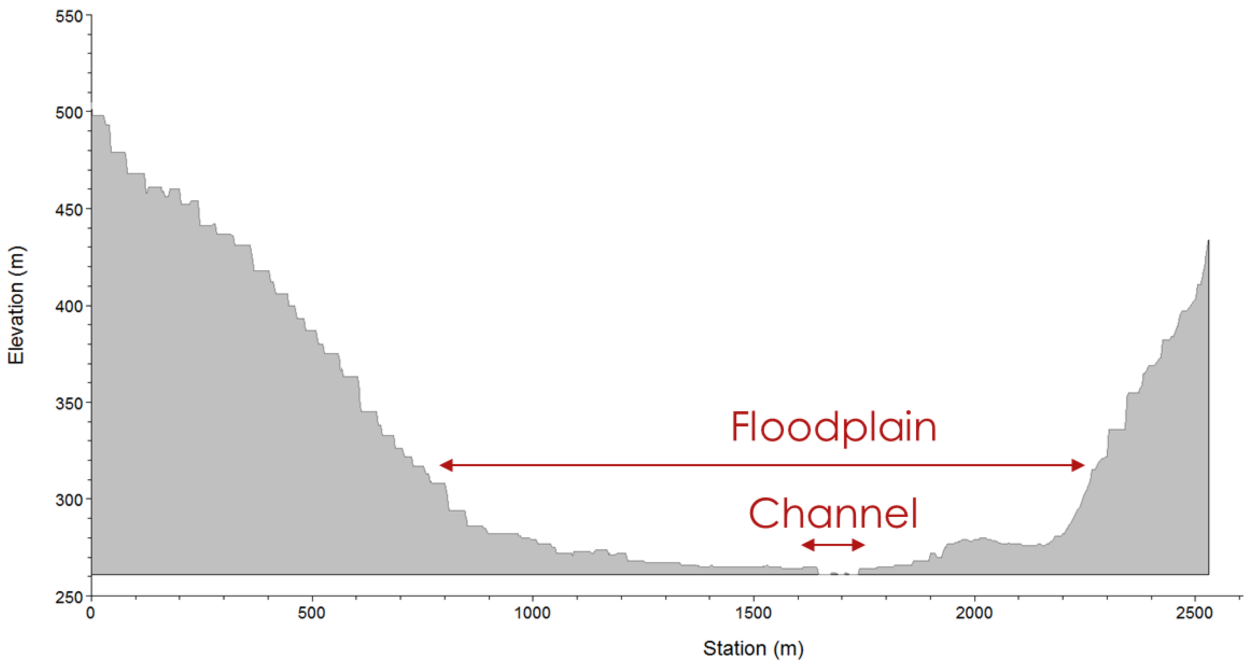

Figure 2.1: Cross section of a river valley illustrating the change in cross sectional area that water flows through during normal and flooding conditions

2.4 Case Study

With the continued changes in global climate, population, economic development, and technologies, water resource managers and planners must adapt to new risks and vulnerabilities, and these risks will be addressed with a combination of structural and non-structural techniques (L.R. Johnston Associates, 1992; Melillo, Richmond, & Yohe, 2014; Moore, et al., 1997).

The Connecticut River Basin is New England's largest watershed extending from Canada through Vermont, New Hampshire, Massachusetts, and terminating in Connecticut. People living in the Connecticut River basin have been impacted by many major storm events. In 2011 Hurricane Irene devastated areas of the US Northeast. Vermont sustained damages to over 500 miles of roadways and 200 bridges, costing upwards of $250 million. The hurricane isolated several towns from emergency services and relief aid for many days. Other impacts from the storm include agricultural losses and inundation of wastewater systems that released untreated sewage and harmful sludge into the environment (Horton, et al., 2014). Many smaller and more frequent events pose a risk to people and property in the Connecticut River Valley.

In the section of the Connecticut River examined in this study (Figure 2.2), a 10-year storm event can flood crop fields, buildings, and roadways. This research explores how changes in the floodplain and potential future flow regimes will impact flooding in the northern portion of the Connecticut River, in a floodplain termed the Maidstone Bends.

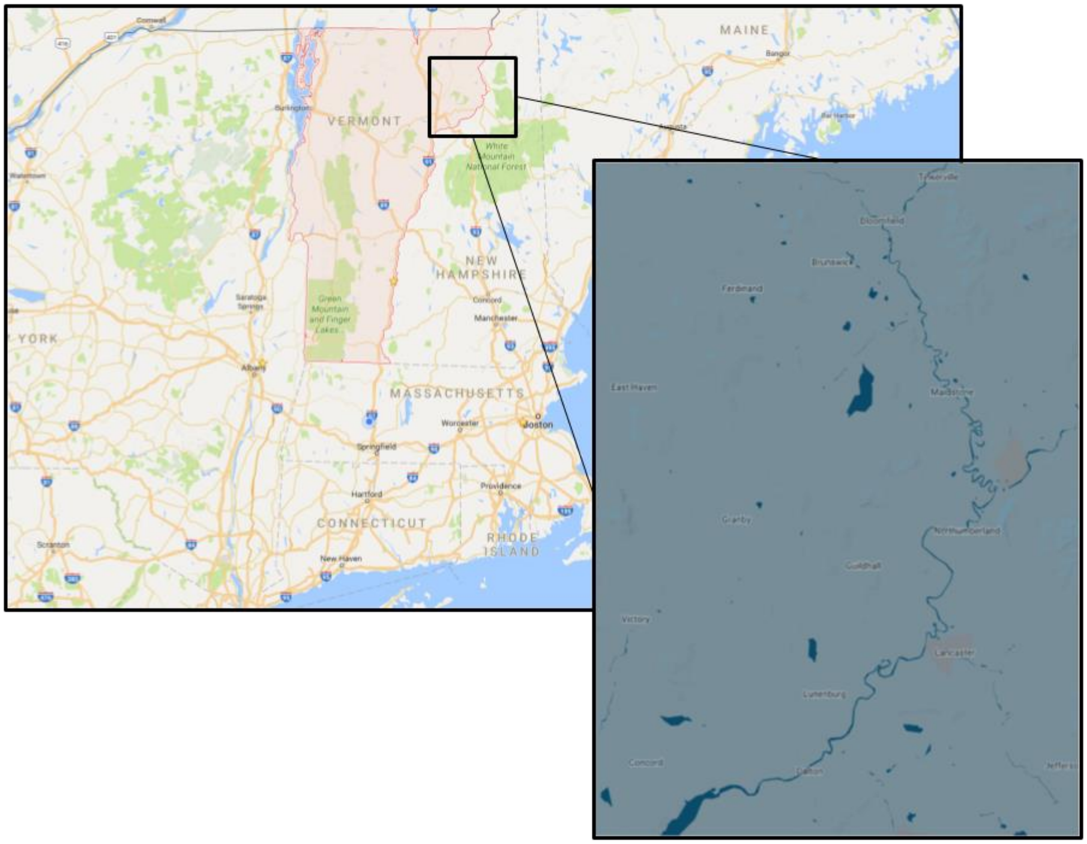

Figure 2.2: The study area for this research (Google Maps, 2017; Google Maps, 2017)

This portion of the Connecticut River meanders approximately 45 river miles and extends from Brunswick, VT to Lancaster, NH. The floodplain is approximately a mile and a half wide. The river flows over relatively flat land and historically overtops its banks during flood events. The section of river under study is not obstructed by large flood control structures like levees and dams. Although most of the floodplain area is forested, the land adjacent to the Connecticut River is agricultural and is impacted by flood waters during flood events (Table 2.3) .

Table 2.3: Percent land use/land cover for the Maidstone Bends region (Homer, et al., 2015)

	Percent Existing Conditions
Barren land	0.08%
Cultivated crop	1.90%
Deciduous forest	37.19%
Developed, high intensity	0.06%
Developed, low intensity	0.91%
Developed, medium intensity	0.28%
Developed, open space	2.07%
Emergent herbaceous wetlands	0.35%
Evergreen forest	14.31%
Grassland/herbaceous	0.54%
Mixed forest	29.29%
Open Water	1.31%
Pasture/hay	1.35%
Shrub/scrub	4.57%
Woody wetlands	5.78%

There are many concerns about the integrity of the Connecticut River's ecosystems. Species such as the tiger beetle, wood turtle, freshwater mussels, silver maple and green ash are dependent on the floodplain habitat of the upper Connecticut River (Gangloff & Feminella, 2006; Hudgins, 2011; Marks, Nislow, & Magilligan, 2014; Sherwood & Wu, 2012). The health, longevity and fecundity of many of these species could be enhanced by improvements to floodplain habitat. Changes to the current habitat through development or restoration could have dramatic impacts to these species, which are already potentially facing challenging times as other climate change impacts bring threats to their survival.

3.0 Methodology

3.1 Experimental Design

This research investigates the relationship between floodplain characteristics and flood flows. It also investigates the impact that climate change may have on flood flows. The research results can provide managers, planners, and conservation groups with crucial information and assessment of the impacts of changes in the floodplain to storm events. The Connecticut River Basin is of interest because of its crucial importance to commerce, recreation, and habitat in the U.S. Northeast. The research's goal is to provide a better understanding of how changes in the floodplain will affect both the flood event at the downstream city of Lancaster and the habitat for ecologically threatened and endangered species within the floodplain. The results from this research can help inform managers and conservationists of ways to maintain and improve the natural environment for both flood management and ecological integrity. To accomplish this research goal, a hydraulic model of the Connecticut River is developed and a variety of land cover and flow regime scenarios are explored to determine their impact on the flood event. Three storm hydrographs representing three return intervals, 1-yr, 10-yr, and 100-yr, are used as inputs to the model for each scenario, and the differences between the scenarios are tracked as a set of seven key metrics, as discussed in section 3.1.2.

3.1.1 Model Scenarios

Various scenarios were developed in collaboration with the members of a interdisciplinary team, and can be found listed in Table 3.1. Scenarios were developed to represent three basic concepts: loss of floodplain, restoration of the floodplain, and future climate impacted flows.

Table 3.1: List of scenarios run with the HEC-RAS 2D model. Each scenario is run at three return internals: 1-yr, 10-yr, and 100-yr.

Number	Name	Description

1	Existing Conditions	Estimated values to calibrate model most closely to aerial photographs
2	Forest as field 100%	All forest land cover types changed to cultivated field type
3	Field buffer	The land adjacent to the river changed to field type
4	Field as forest 100%	All field land cover types changed to forest type
5	Forest buffer	The land adjacent to the river changed to forest type
6	Theoretical Restoration	Restoration in the floodplain along the mainstem and along the tributaries
7	Theoretical Development	Development in the floodplain along the mainstem and along the tributaries
8	Increased storm frequency	Two storm events run in succession under estimated range of existing conditions

The existing conditions scenario established through model calibrations to establishes current conditions of the floodplain. The storms selected for analysis demonstrate how the floodplain behaves under current conditions. This sets the baseline for comparison in modeled changes to the floodplain. Scenario 2 addresses how the floodplain would interact with flood flows if all the forest in the floodplain was converted to agricultural lands. This is of interest to stakeholders here because in the Maidstone Bends area deforestation would likely be a result of agricultural development. Similarly, scenario 4 explores what would happen if all agriculture was returned to forest ecosystems. Returning agricultural lands to their native forests is one of the easiest developed LULC type to change because there are typically less people per acre impacted and there are limited structures that would need to be dismantled. Scenarios 3 and 5 investigates the two extremes of complete deforestation and complete restoration along a buffer of land closest to the river's edge. While this is an unrealistic expectation, it sets a bound for the possible attenuation impacts to a flood event; these scenarios produce the maximum and minimum flood peaks without changing access to the floodplain (i.e. levees that block off access to part of the floodplain). The results from these two scenarios highlight a potential for a flood management plan that establishes floodplain corridors along river edges to minimize economic impact associated with reclaiming developed lands while increasing flood attenuation in this river reach. Scenario 6 addresses the question of how the flood flows would react if levees were built along the river's edge. The river currently does not have a levee system in this stretch of river, but economic and societal pressures could change this in the future as farmers and nearby residents request structural protection within the floodplain. Given the relatively narrow extent of the floodplain over a long river reach, overall changes to a flood event can be limited; scenarios 6 and 7 investigate expanding the model to incorporate changes to the floodplain along the tributaries that feed into this river reach. Due to the limited availability of flow data, these scenarios were not based on the historic record, but were instead estimated as a means of analyzing potential impacts changes along the tributaries would have on a flood event. Finally, scenario 8 explores the impacts of more frequent and intense storms in the area, which is a concern the stems from the potential impacts due to climate change. Floodplains have the potential to attenuate flows such that a later flood event is larger and more destructive than it would have been had the floodplain not attenuated flows from the first event. With climate projections indicating more frequent storms, how the Maidstone Bends floodplain reacts to frequent events is crucial information for stakeholders.

Each scenario was developed to investigate how a change in the floodplain will impact a flood event. Combined, the scenarios establish the upper and lower limits of possible changes within the Maidstone Bends floodplain and highlight several realistic alternate future conditions. The results from these scenarios will produce the bounds of potential impact of both further floodplain development and floodplain restoration on flood risk and improving ecological integrity of the floodplain habitat in this area.

3.1.2 Metrics

Based on past research, five key metrics for each scenario were used to measure change: 1) Discharge, 2) Depth, 3) Time of Arrival, 4) Flooding duration, 5) number of buildings flooded.

Discharge is the metric used to measure peak flood, and is the rate of the volume of water moving through the system. Discharge is related to velocity and depth, which are two other metrics considered in this research. Typically, flood managers want to minimize the peak flow at any location at-risk.

Depth of flooding is a key explanatory variable in determining the spatial extent of flooding and is related to property damage (particularly when combined with flow velocity (Kreibich, et al., 2009). Changes in flood depth impact zoning and flood insurance. If flooding within the floodplain is encouraged, then development within the floodplain must be restricted to higher elevations to protect from damages.

Changes in the time of arrival of a flood wave impact how much warning communities have to take protective measures. Across the country early warning systems for floods are improving, as these systems increase the time between notice of a pending event and the flood event to allow communities to take measures that save lives and protect infrastructure and property, thereby potentially reducing damages (Sorensen, 2000). By reducing the time of arrival of a flood event, early warning systems will provide more notice, thereby reducing flood damages.

Flooding duration is an important ecological metric. Many floodplain species have flooding requirements that include multi-day flood events on an annual or biennial basis (Marks, Nislow, & Magilligan, 2014). Increase in flooding duration within the floodplain can increase habitat suitability for many threatened and endangered floodplain species.

Finally, the number of buildings impacted by floodwaters is a crucial factor to compare, as it represents both flood risk and economic impact. This metric informs how much flooding occurs within the floodplain. While there are less inhabitants within the Maidstone floodplain as compared to the at-risk population downstream, restoration efforts increase flooding within the floodplain leading to an increased risk to life and property for people who currently reside in the floodplain. Despite the many benefits of floodplains, it is important to be aware of and attempt to find solutions to minimize the disadvantages of flood events in the floodplain.

These five metrics evaluate scenarios and quantify the impacts of floodplains. Allowing a floodplain to flood naturally to reduce risk to downstream inhabitants has an impact on the infrastructure currently in the floodplain. These metrics help explore the trade-offs between the benefits and disadvantages of utilizing this flood management technique.

3.2 Model Selection

There are many hydraulic and routing models that can evaluate how metrics of interest, such as how much flow at Lancaster, NH, changes with changing floodplain and inflow conditions. This project investigated several tools before selecting a HEC-RAS 2D model for analysis of scenarios of interest and identification of restoration locations.

3.2.1 HEC-ResSim

The first software utilized in this research was the U.S. Army Corps of Engineers [USACE], Institute for Water Resources, Hydrologic Engineering Center's Reservoir System Simulation [HEC-ResSim]. This software uses unique operation and routing rules to simulate how reservoirs operate for flood management.

A floodplain can be conceptualized as a large reservoir with an uncontrolled weir outlet. Discharge-Stage-Storage relationships can be calculated from existing data to represent the relationships of flow leaving the floodplain at a certain location. This simple definition of how a floodplain functions suggests that in the HEC-ResSim software, floodplain capacity can be modeled as a reservoir with an outlet with the basic release rules.

Because a HEC-ResSim model for the entire Connecticut River Basin had been constructed by the USACE, the application of this model for this research was attractive. This model was used to investigate how increases in the floodplain capacity would impact the flood hydrographs. A discharge-stage-storage relationship was developed using data from an existing HEC-RAS model (from the The Nature Conservancy). This relationship was incorporated as release rules for the Maidstone Bends "Reservoir." Ultimately, it was impossible to validate the results of this model; there is no opportunity to increase the Maidstone Bend's floodplain capacity to calibrate the model and validate the results. Because of the inability to validate results, this modeling method was not selected for final analysis.

3.2.2 HEC-RAS

In early 2016, the Hydrologic Engineering Center formally released HEC-RAS 5.0. This updated version of HEC-RAS introduced two-dimensional modeling of flow to this widely utilized software. This 2D modeling component allowed this research to use HEC-RAS 5.0 to model how flood flow events interacted with the floodplain as it moved through it. This is done using either the Full Saint Venant or Diffusion Wave equations. The Diffusion Wave equations are typically more stable and can be computed on a larger computational time-step, but the Full Saint Venant equations are more accurate and may be needed in complex cases, such as mixed flow regimes.

This updated modeling software has two options for modeling river and floodplain flow, a 1D/2D interface model, or a strict 2D model (Table3.2). Each option was explored in this research and, after careful exploration into both options, the 2D HEC-RAS software was selected as most appropriate. A 1D model was not considered for this application due to the inability to model multi-directional flows in wide floodplains.

Table 3.2: Differences between each type of HEC-RAS model

	HEC-RAS 1D	HEC-RAS 1D/2D	HEC-RAS 2D
Geometric data	River system schematic, cross section data (station vs elevation, downstream reach lengths, Manning's roughness coefficient values for banks and channel, contraction and expansion coefficients)	River system schematic, cross section data (station vs elevation, downstream reach lengths, Manning's roughness coefficient values for banks and channel, contraction and expansion coefficients), digital elevation model, land cover, lateral connection data (station vs elevation, structure type, HW and TW connections)	Digital elevation model, land cover data
Boundary Conditions	Upstream reach, downstream reach	Upstream reach, downstream reach	Upstream floodplain, downstream floodplain
Initial Conditions	Flow data	Flow data, wse in 2D flow area	Flow data, wse in 2D flow area
Results	Simple water surface elevations, hydrographs at cross sections	Simple water surface elevations, flood wave progression in multiple direction, hydrographs at any point of interest within the floodplain	Simple water surface elevations, flood wave progression in multiple direction, hydrographs at any point of interest within the floodplain
Suitability	Flow is uni-directional, simple river-floodplain connections, limited elevation data	Flow expected to spread (multi-directional), wide floodplains, wetland studies	Flow expected to spread (multi-directional), wide floodplains, wetland studies
Run time	Fast	Slow	Slow

Initially a 1D/2D model was developed for this research. This model was 1-dimensional in the river channel, and 2-dimensional in the floodplain. The two portions of the model were connected using a lateral structure, in the case of this location, inputted at ground level based on the terrain data. Data for the 1D model included Manning's roughness coefficient values for the channel and river bank, and cross section data at sufficiently frequent locations along the 45-mile stretch of river. These data were collected from the field, which entailed utilizing sonar technology and other surveying equipment (stadia rod, measuring tape, boat), to collect cross section data in the river. Initially, researchers collected data for ten cross sections as a starting place for modeling. The 2D portion of the model required digital elevation models [DEMs] of the area, 1-meter Light Detection and Ranging [LiDAR] for the Vermont side of the river and 2.5-foot LiDAR for the New Hampshire side. Land cover data from the National Land Cover Database [NLCD] was incorporated and initial Manning's roughness coefficient values were associated with each land cover type. The range of Manning's roughness coefficient values were selected through analysis of the literature (Table 3.3). The data were incorporated into the model and additional cross sections were interpolated based on the field collected data. Gage data from The United States Geological Service [USGS] was incorporated as the upstream boundary condition. For the downstream boundary condition, the normal depth condition based on the slope energy grade line was used. However, despite multiple attempts, researchers were unable to achieve model stability and reliable results.

Table 3.3: The range of Manning's roughness coefficient values for land cover found in literature (Natural Resources Conservation Service, 2016; Chow, 1959; Phillips & Tadayon, 2007; Natural Resources Conservation Service, 1986; Kalyanapu, Burian, & McPherson, 2009; Arcement, Jr. & Schneider, 1989).

	Min	**Max**	**Model Existing Conditions**
Barren land	0.011	0.1227	0.023
Cultivated crop	0.02	0.17	0.02
Deciduous forest	0.08	0.8	0.16
Developed, high intensity	0.011	0.0404	0.03
Developed, low intensity	0.011	0.12	0.12
Developed, medium intensity	0.011	0.08	0.08
Developed, open space	0.011	0.06	0.06
Emergent herbaceous wetlands	0.05	0.1825	0.085
Evergreen forest	0.08	0.8	0.16
Grassland/herbaceous	0.025	0.368	0.025
Mixed forest	0.08	0.8	0.16
Open Water	0.001	0.05	0.025
Pasture/hay	0.025	0.41	0.025
Shrub/scrub	0.035	0.4	0.07
Woody wetlands	0.045	0.335	0.045

The inability to achieve model stability in the HEC-RAS 1D/2D model lead to the development of a HEC-RAS 2D model, which was built in HEC-RAS 5.0.3, the newest version of HEC-RAS at the time of this research. This 2D model incorporates the NLCD with the associated Manning's roughness coefficient values (Table 3.3). Like the HEC-RAS 1D/2D model, the 2D model requires a DEM for the region as an input. Unlike the 1D/2D model, however, the 2D model does not incorporate channel geometry including bathymetry or channel specific Manning's roughness coefficient values. Because the DEM data doesn't penetrate water, the digital elevation models do not incorporate the river channel. Thus, the full river geometry is not captured and the river channel is modeled at a reduced capacity. While this will produce a source of error in the model results, in-channel flows are sufficiently small, as compared to the storm events this research investigates, to be considered negligible.

The two 2D model uses USGS stream flow data from the North Stratford, NH (01129500) gage as the upper boundary input and a normal depth associated with the energy slope grade line as the lower boundary condition.

3.2.2.1 Selection of an Equation Set

The 2D model computes two dimensional, unsteady-flow using a set of continuity and momentum equations, where variables can be calculated with the Diffusion Wave set of equations (considered numerically more stable) or with the 2D Full Saint Venant set of equations, (considered to be more accurate over a wider range of modeling applications). Selection of the appropriate equation set with is based on the ability to achieve model stability, computational time, differences in accuracy between the two sets, and model application. Although both were tested for initial conditions, due to minimal differences in solutions and larger computational time steps, the Diffusive Wave equation set was selected to perform model runs (Brunner, 2014).

Continuity Equation

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

Momentum Equation

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} = S$$

For the Diffusion Wave Equations:

$$S = \left(S_0 - S_f\right)$$
$$E = huv$$
$$G = huv$$
$$U = hu$$

For the Full Saint Venant Equations:

$$S = \left(S_0 - S_f\right)$$
$$E = hu^2 + \frac{gh^2}{2}$$

$$G = hv^2 + \frac{gh^2}{2}$$
$$U = hv$$

3.2.2.2 Calculating a time step

The model time-step impacts both the stability of the model and computational speed. The time-step needed to be maximized while still maintaining stable results. The starting point for choosing a computational time step is determined using Courant Number equations for each set of equations to solve for flow. From there, various input parameters, including the computation time step, cell size of the 2D-flow area and tolerances were adjusted to achieve full model stability.

For the Full Saint Venant Equations:

$$C = \frac{V * \Delta T}{\Delta X} \leq 1.0$$

Where:
$C = Courant\ Number$
$V = Velocity\ of\ the\ Flood\ Wave\ (ft/s)$
$\Delta T = Computational\ Time\ Step\ (second)$
$\Delta X = average\ cell\ size\ (ft)$

For the Diffusion Wave Equations:

$$C = \frac{V * \Delta T}{\Delta X} \leq 2.0$$

Where:
$C = Courant\ Number$
$V = Velocity\ of\ the\ Flood\ Wave\ (ft/s)$
$\Delta T = Computational\ Time\ Step\ (second)$
$\Delta X = average\ cell\ size\ (ft)$

3.2.2.3 *Calibration and Establishing Existing Conditions*

All hydraulic models must be calibrated to verify that the model produces accurate results. The Nature Conservancy provided aerial photographs of two flood events (April 2011 and March 2010), that span the study area limits. The flooding extent from these events were mapped using these aerial images (Appendix A). Then, the gage data for each of the storms were run through the model. The model results of predicted flooding extent were then compared to the aerial image derived extent. During these runs the Manning's roughness coefficient values were adjusted within the literature-defined range to calibrate the model to these two storm events. The Manning's roughness coefficient values were optimized within the literature defined range to minimize the error between the two storm events, and flooding extent difference of <10% was achieved to establish existing calibrated conditions. Once the Manning's roughness coefficient values for existing conditions were established, a suite of various storms representing the 1-yr, 10-yr, and 100-yr return intervals were run through the model. These three storm events establish a baseline for how the existing floodplain currently functions.

4.0 Results and Discussion

4.1 Mainstem Floodplain Scenarios

This research's goal is to analyze how different changes to the floodplain will impact flood events for downstream inhabitants of the Connecticut River. The scenarios described in section 3 cover a wide range of possible changes and were run using the HEC-RAS model for three storm events, a 1-year return interval, a 10-year return interval, and a 100-year return interval. The five key metrics from section 3 are compared to evaluate the state of flood events under each scenario. Table 4.1 describes these five key metrics over the range of storm return intervals for all LULC scenarios in the mainstem of the river.

Table 4.1: Change in the time of the peak flow from existing conditions, the maximum peak flow, the maximum stage, and the change in percent of peak flow from existing conditions for each of the three storm events

1 yr RI						
Scenario	Max Peak Flow (m3/s)	Percent Change Flow	Max Stage (m)	Change in Peak Arrival (hours)	Change in Flood Duration (hours)	Change in # of buildings flooded
Existing	256.49	--	259.18	--	0	--
Field as Forest	247.26	-3.60%	259.84	12	0	16
All Forest	235.26	-8.28%	260.05	22	7	49
500m Forest Buffer	235.26	-8.28%	260.05	22	7	49
250m Forest Buffer	237.89	-7.25%	259.88	18	5	28
100m Forest Buffer	241.12	-5.99%	259.41	12	0	20
Forest as Field	263.5	2.73%	258.88	-11	-29	-7
All Field	263.68	2.80%	258.8	-16	-36	-19
500m Field Buffer	263.7	2.81%	258.81	-16	-36	-19
250m Field Buffer	264.16	2.99%	258.91	-15	-35	-15
100m Field Buffer	263.27	2.64%	259.03	-14	-35	-13

10 yr RI						
Scenario	Max Peak Flow (m3/s)	Percent Change Flow	Max Stage (m)	Change in Peak Arrival (hours)	Change in Flood Duration (hours)	Change in # of buildings flooded
Existing	503.24	--	259.73	--	0	--
Field as Forest	482.66	-4.1%	260.64	6	10	12
All Forest	456.99	-9.2%	260.89	10	29	33
500m Forest Buffer	459.21	-8.7%	260.85	9	29	24
250m Forest Buffer	472.43	-6.1%	260.67	7	27	23
100m Forest Buffer	487.76	-3.1%	260.1	2	14	15
Forest as Field	507.49	0.8%	259.62	-1	-1	0
All Field	539.33	7.2%	259.24	-6	-9	-12
500m Field Buffer	539.16	7.1%	259.23	-5	-9	-12
250m Field Buffer	539.11	7.1%	259.28	-5	-9	-11
100m Field Buffer	515.25	2.4%	259.95	-2	-4	0

100 yr RI						
Scenario	Max Peak Flow (m3/s)	Percent Change Flow	Max Stage (m)	Change in Peak Arrival (hours)	Change in Flood Duration (hours)	Change in # of buildings flooded
Existing	790.12	--	260.35	--	--	--
Field as Forest	748.76	-5.23%	261.34	7	9	
All Forest	692.39	-12.37%	261.59	12	21	130
500m Forest Buffer	697.24	-11.76%	261.54	11	20	125
250m Forest Buffer	724.06	-8.36%	261.33	8	19	118
100m Forest Buffer	762.89	-3.45%	260.73	3	16	26
Forest as Field	800.1	1.26%	260.13	0	0	--9
All Field	850.29	7.62%	259.61	-6	-4	-40
500m Field Buffer	850.08	7.59%	259.62	-6	-4	-36
250m Field Buffer	840.28	6.35%	259.8	-5	-3	-27
100m Field Buffer	838.04	6.06%	259.91	-4	-3	-15

For each return interval, a similar and consistent pattern of changes in the metrics emerges. As the forest land cover is increased, peak flow is decreased (Figure 4.2) while depth, time of arrival, duration, and number of buildings flooded increases. The reverse is true when field land cover is increased, with peak flow increasing and the other four metrics decreasing. Of note, due to the existing land cover distribution, there are only minor changes between the All Forest and 500m Forest Buffer. In this area of Vermont, further away from the Connecticut River, human development decreases and LULC is mainly forested while most human development is concentrated close to the river's banks. Because restoration opportunity decreases, and because the land closest to the river floods most frequently, model changes representing restoration LULC are most impactful near the banks of the river and their impact decreases further out into the floodplain. The metrics between the All Field and 500m Field Buffer are also similar for all three storm events. Due to the flooding extent of the most common storms, not extending further into the floodplain. However, under certain conditions flood events that have a greater flood would likely show greater differences in metrics. These behaviors are consistent with prior research and indicate that there is potential for planners, managers, and NGOs to have an impact on the flood event in this section of the Connecticut River.

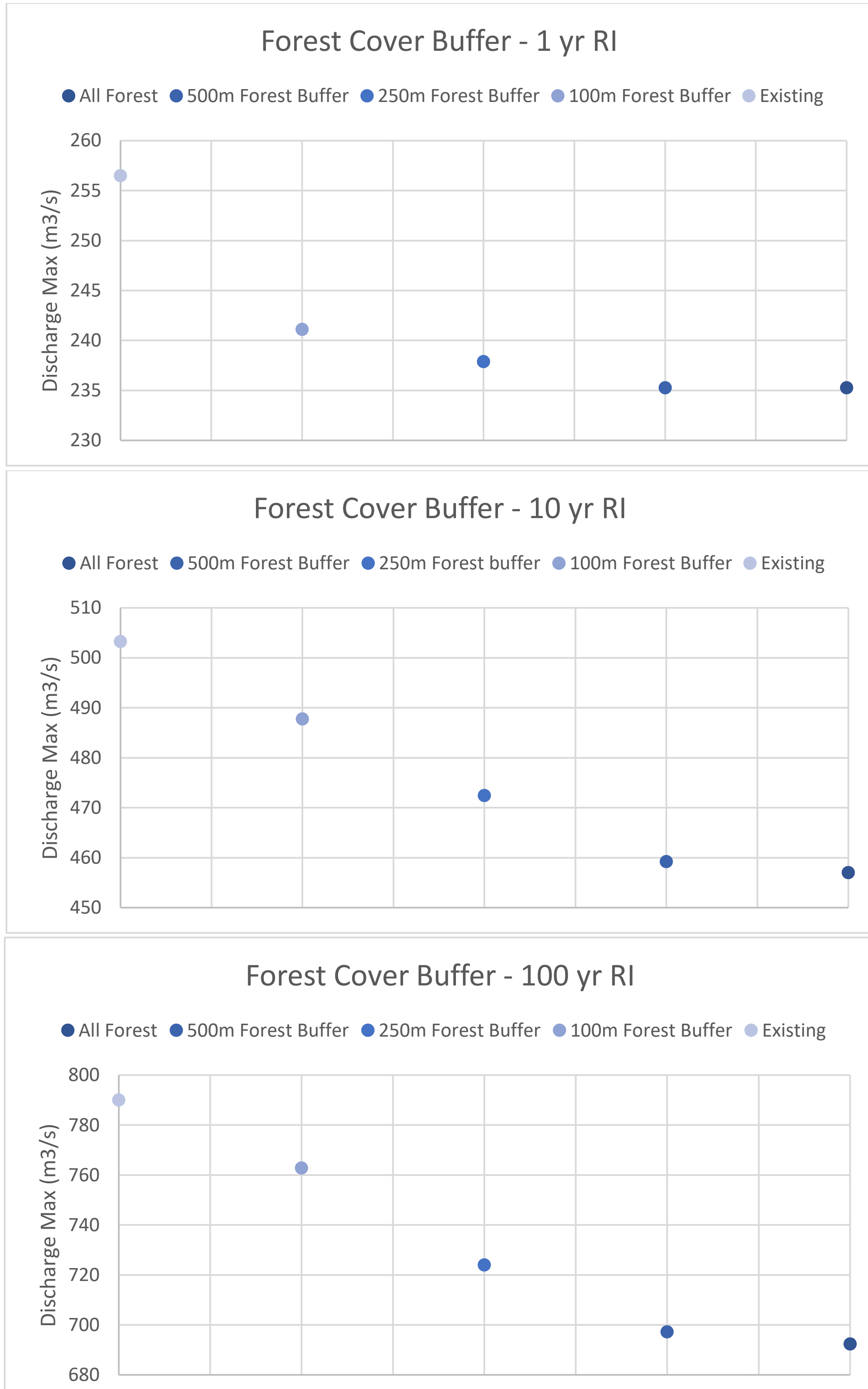

Figure 4.2: Change in peak flow for forest cover levels for each flood event (1yr, 10yr, 100yr)

4.1.1 Reforestation under 1, 10, and 100-year return intervals

Both the peak flow, and change in flood arrival time metrics indicate that increased floodplain forests could reduce flood risk for downstream inhabitants. Reforestation along the mainstem of the Connecticut River would have an impact of 3 to 12% reduction in the peak flow and up to 29 hours additional warning time from existing conditions. Results indicate that there is potential to reduce maximum flows with smaller land changes. All three storm intervals show that with changing forest buffers, the maximum discharge decreases until approximately the 500m mark, and that there is minimal change between a 500m forested border and converting the entire floodplain to forest (Figure 4.2). The similarity in flood event between the 500m Forest Buffer and the All Forest scenarios is due to the extent of flooding. Larger events not tested in this analysis would likely flood further into the floodplain and thus there would be larger differences between the 500m Forest Buffer and All Forest scenarios. However, for the most common storms, conservation and restoration efforts beyond 500m from the center line of the river would have negligible impact on the flood event. Although results show that floodplains do not fully attenuate flood flows, they represent an opportunity to reduce a portion of risk within a broader, more complete flood risk management plan.

Because the number of days a floodplain forest is flooded is crucial to maintaining ecological integrity within the floodplain, this analysis shows there be more land for habitat by restoring floodplain forest areas. Managers might be inclined to only select sites of restoration where the appropriate duration and periodicity of flooding for floodplain forests already occurs. However, these results indicate that restoration of these forests in areas that don’t currently have the appropriate environment could create the necessary conditions for floodplain forest habitat, expanding the options for floodplain forest restoration efforts. There is an increase in the flood duration metric with a potential gain of up 42 additional hours of flooding per storm event when the floodplain has been converted forest as compared to current conditions (Table 4.1).

One consequence of floodplain restoration suggested in these results is the impact to people currently residing within the floodplain. By promoting flooding within the floodplain, those properties will flood more often, as indicated by the change in the number of buildings flooded. While any flooding of property is undesirable, increasing the flood risk in a low populated floodplain might be considered worth the decrease in flood risk to a higher populated area downstream of the floodplain. This trade-off would need to be carefully considered by interested organizations, and could be mitigated through incentive programs that encourage people to move beyond the floodplain extent.

4.1.2 Comparison of Metrics: 250m Land Cover Buffer

Figure 4.3 illustrates how peak flow, time of arrival, and duration would change from existing conditions if land cover changed to become more forested or more agricultural for the ten-year flood event. This case specifically illustrates the difference between existing conditions, a 250m forested buffer as measured from the river's centerline, and a 250m agricultural buffer.

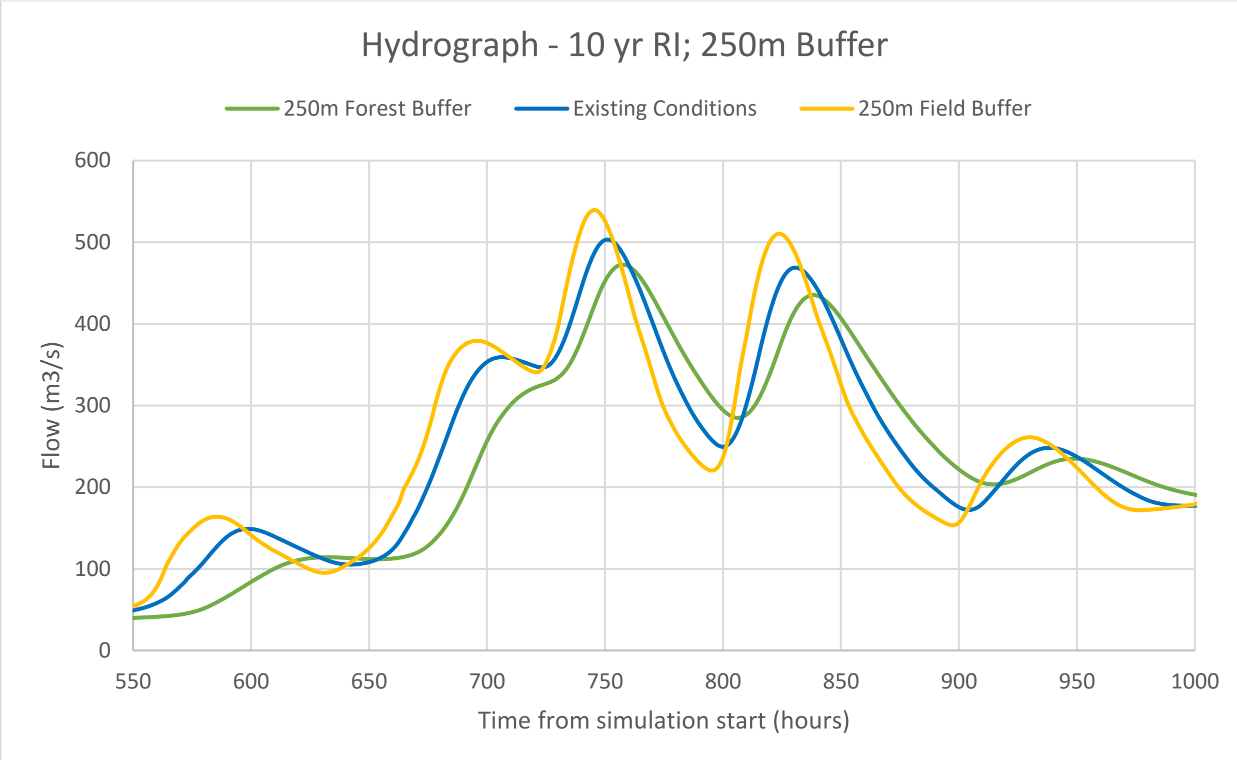

Figure 4.3: Hydrograph of existing conditions, 250m forest buffer, and 250m field buffer

This hydrograph illustrates the change in the flow for these scenarios, with a 13-percentage point difference between the field and forest scenarios in the change in peak flow from existing conditions. It also illustrates that under forested conditions, the flood event occurs later as compared to both the field and existing conditions, by 36 and 27 hours respectively. The hydrograph also indicates that the flooding occurs over a longer period as compared to the field scenario and existing conditions case, which as discussed earlier, increases the potential habitat suitability.

Similarly, Figure 4.4 shows water stage for this scenario. Stage has a direct impact on the flooding extent of the water, and these results indicate that with a forest buffer, flood water is attenuated, increasing the depth and allowing water to reach higher elevations in the floodplain. Conversely if the adjacent land was transformed to agriculture, there would be less resistance to the flow of water. Because of this, water would move faster and would not linger in the floodplain reducing flood peak height and flooding extent within the floodplain. However, this would result in higher peak flows, faster arrival times, and shorter flood durations, which increases flood risk to downstream inhabitants and negatively impacts habitat for floodplain species.

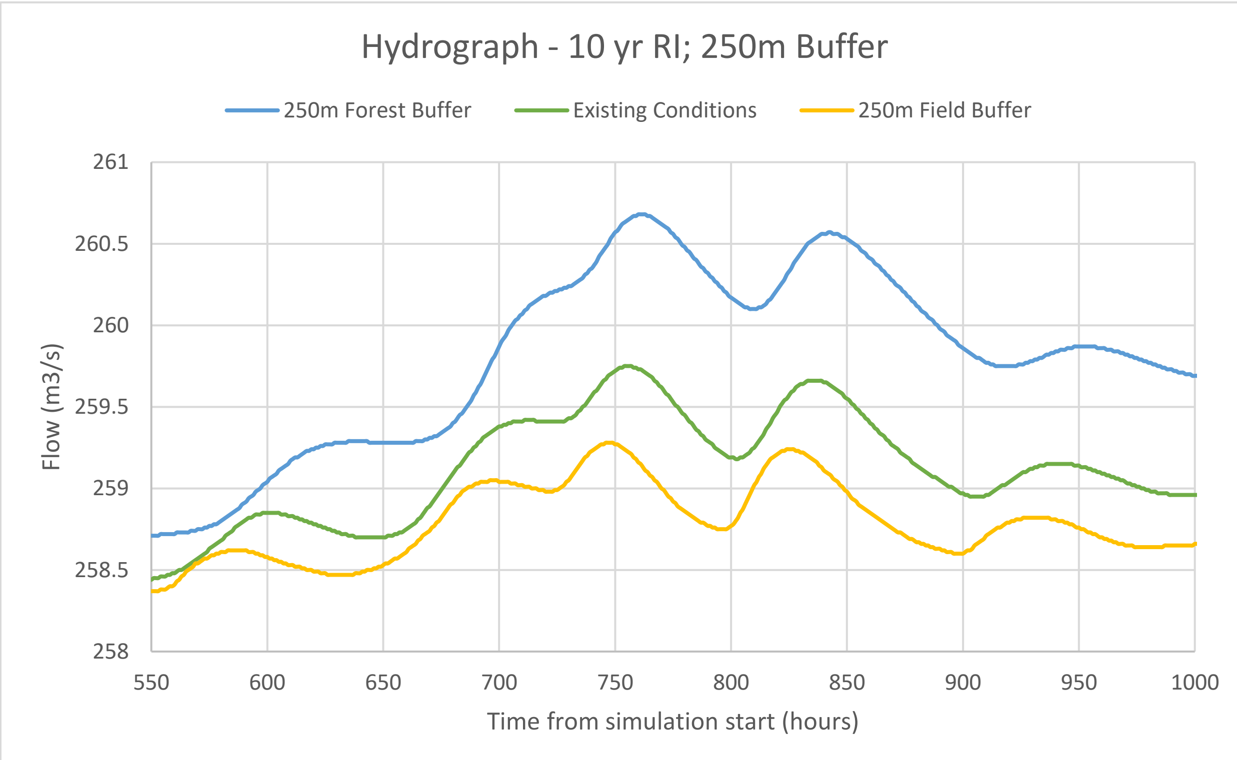

Figure 4.4: Stage of existing conditions, 250m forest buffer, and 250m field buffer for 10yr RI

Approximately 4500 acres of land is required to create a 250m buffer at the edge of the river along this section of the Connecticut River Given the reported price of land in Vermont in 2015, this purchase would cost upwards of $14.8 million to acquire (National Agricultural Statistics Service, 2015). Interested stakeholders would want to investigate these graphs for each set of scenarios (Appendix B) before selecting a restoration effort that best fits their management goals and resource availability.

4.2 Mainstem and Tributary Theoretical Scenarios

Along the tributaries in the Maidstone Bends section of the Connecticut River, current LULC conditions are mostly forested along the tributaries, however, there is concern that development could lead to the deforestation of the floodplain ecosystems to make way for additional agricultural lands. Addressing these concerns, however, posed a challenge for analysis because of the lack of historic stream flows for the tributaries. To analyze how LULC changes would impact the flood event representative flows that are proportional to the mainstem steam gage data from the 10-year return interval are incorporated into the model for each tributary. The three scenarios analyzed were Existing Conditions, All Forest, and All Field. While stakeholders would likely make much smaller changes to the floodplain, these scenarios were developed and run to generate the broadest scope of possible change due to changes in the LULC of the tributaries and the mainstem.

Table 4.5: Five key metrics for theoretical scenario 10 yr RI

Scenario	Max Peak Flow (m3/s)	Percent Change Flow	Max Stage (m)	Change in Peak Arrival (hours)	Change in Flood Duration (hours)	Change in # of buildings flooded
Existing Conditions	903.62	--	260.38	--	--	--
All Field	956.93	5.9%	259.66	-6	-21	-19
All Forest	796.43	-11.9%	262.72	12	10	132

The results of this analysis (Table 4.5) are consistent with the prior analysis and indicate that efforts to restore floodplain forests in the both the tributaries and the mainstem would reduce flood peaks, and increase stage, arrival time, duration, and number of buildings flooded. Whereas further development would increase peaks, and decrease the other four metrics.

The hydrograph, and stage vs time graph the theoretical scenarios are found in figures 4.6 and 4.7.

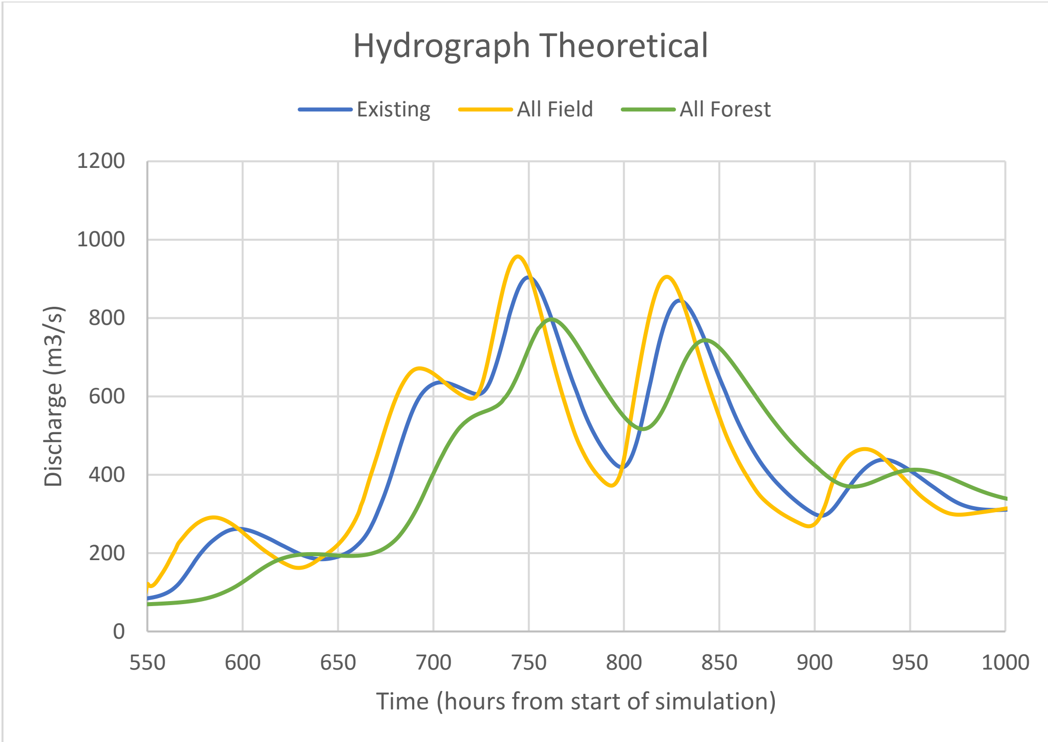

Figure 4.6: Hydrograph of theoretical storm event

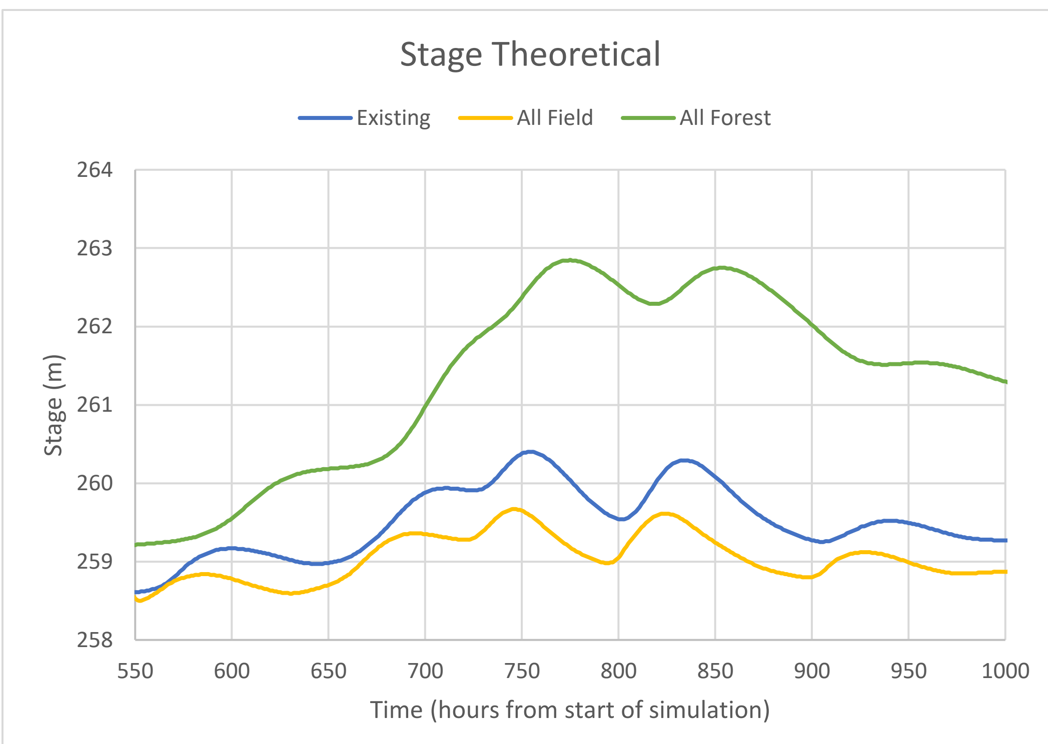

Figure 4.7: Stage vs Time of theoretical storm event

These graphs illustrate how flows are impacted by changes to the LULC in both the mainstem and the tributaries. Results indicate that, as expected, flood peaks decrease with restoration and increase under the development scenario. Likewise, stage, time of arrival, duration, and number of buildings flooded increase with restoration and decrease with development. In the case of the Maidstone Bends and its tributaries, the peak flow could change up to 18-percentage points between the fully agricultural and fully forested scenarios. Another metric of note is the change in number of buildings flooded metric under the Theoretical All Forest scenario. The results from this scenario show that four times the number of buildings would be flooded as compared to the All Forest scenario that only changes LULC along the mainstem of the Connecticut River. This metric shows that further restoration in the floodplain tributaries would lead to much larger human and economic impacts than any other scenario while still achieving similar levels of flood risk reduction.

These results indicate that potential land use changes in the tributaries should be focused on preservation of floodplain forests, while mainstem activities would entail more reclamation and restoration of land to floodplain forests. These differences pose different challenges to managers and conservation groups. Given the scope of different stakeholders these results can direct stakeholders toward the appropriate action that can be the most effective toward achieving their goals.

4.3 Increased Storm Frequency

Modeling how climate changes will impact floodplain responses to flood events can be a complicated and challenging task. There exist many techniques and models to simulate climate impacted flow. This research uses a simple technique to explore the floodplain's response to more frequent storm events by incorporating flow from two identical storm events occurring in close succession. This was selected because of the potential for increases in storm frequency under climate change in the U.S. Northeast.

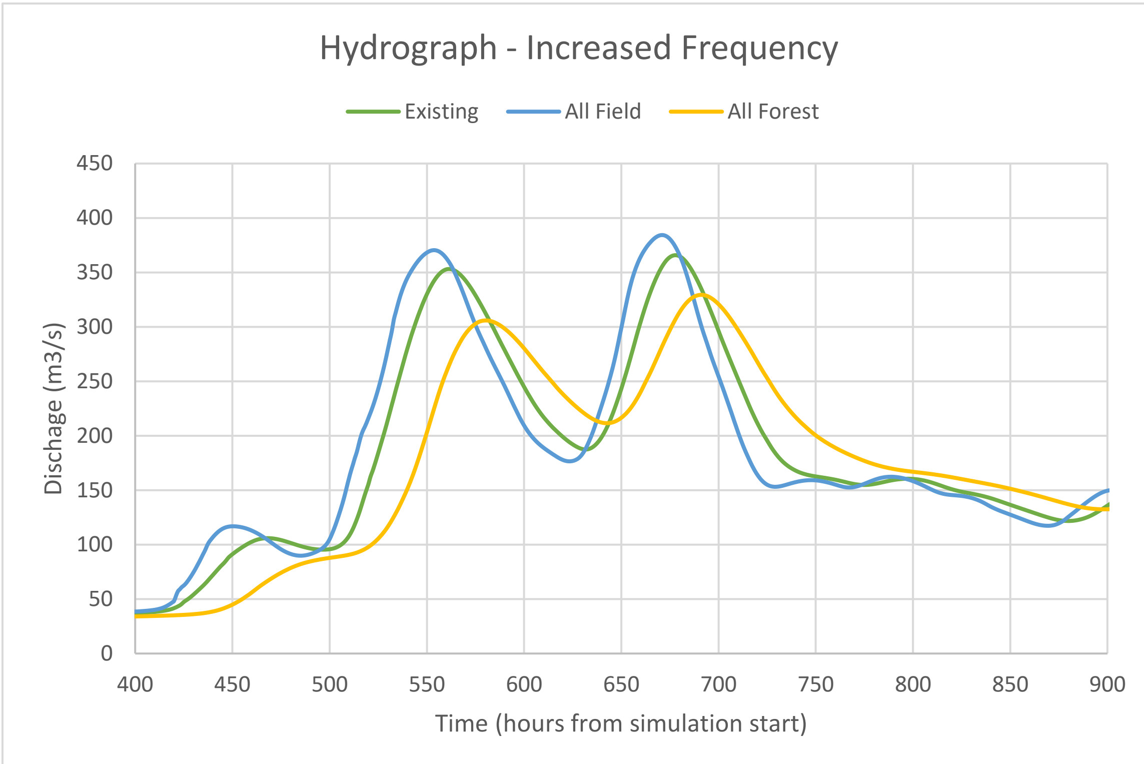

Figure 4.8: Hydrograph of double flood event at the 2 yr recurrence interval

While there are many more future climate flow scenarios to explore, this analysis specifically investigates how the second event of two storms in close succession changes with LULC changes within the floodplain (Figure 4.8). The All Field and All Forest scenarios were assessed to address the broadest possible changes in metrics.

One concern with floodplain restoration is the potential for higher flood flows during multiple storm events. This has the potential to occur when a floodplain attenuates flows from the first storm and then another storm follows shortly thereafter. If the floodplain is still flooded from the initial storm and it is not able to attenuate the second storm's flows, during the second event, flow from both storms could contribute and increase the peak beyond what either storm would produce in a highly-developed area.

Table 4.9: Peak Flow and Stage for the flood event under each scenario

Scenario	1st Peak Flow (m3/s)	2nd Peak Flow (m3/s)	Percent difference between 1st and 2nd peaks	Percent Change in 2nd peak flow from Existing
Existing	353.09	365.79	3.60%	--
All Field	370.39	384.3	3.76%	5.06%
All Forest	305.85	329.38	7.69%	-9.95%

The results from this analysis show that the second flood peak is 7.7% percent higher than the first flood peak under the All Forest scenario (Table 4.9). The Existing scenario shows the second flood peak as only 3.6% higher than the first peak flood in the same scenario. Because the floodplain is flooded to greater extents and for longer durations under the All Forest scenario, the floodplain is unable to reduce the peak of the second flood event by as much so that in the All Forest Scenario the flood peak of the second event is proportionally higher to the flood peak of the first event as compared to the Existing scenario. However, the peak flow of the second flood event under the All Forest scenario is still 10% lower than the peak flow of the second flood event under the Existing scenario. Therefore, restoration efforts in the Connecticut River Basin still reduce flood peaks, and thus flood risk for downstream inhabitants even during more frequent flooding events.

5.0 Conclusions

This research investigated the impact that changes in land use and flood frequency in the Maidstone floodplain could have on flood events along the Connecticut River through a wide analysis of potential scenarios and a comparison of key metrics that describe the flood events. The metrics compared were 1) Discharge, 2) Depth, 3) Time of arrival, 4) Flooding duration, and 5) Number of buildings flooded. These metrics were analyzed using a 1-year, 10-year, and 100-year return interval.

The analysis of these current and potential future states of the Maidstone Bends floodplain highlight the promising impact restoration efforts can have on both flood management and ecological integrity. The results also indicate that while complete restoration would have the greatest impact on reducing flood magnitude, smaller restoration efforts could still reduce peaks. Smaller restoration efforts have fewer negative impacts upon the inhabitants within the floodplain, such as relocation and loss of agricultural land use, and would have less economic costs associated with land acquisition of the restoration. However, all restoration efforts increase flood risk metrics to inhabitants of the floodplain while reducing flood risk metrics for downstream inhabitants. Additionally, none of the restoration scenarios showed complete attenuation of flood flows; no restoration efforts would be sufficient as the only means of protecting inhabitants from large flood events. However, well-functioning floodplains can be used alongside other flood management strategies to create more robust flood management plans as well as improve habitat integrity.

Organizations interested in habitat integrity and flood management need site specific information on how best to achieve those goals. Understanding the quantitative difference in potential benefits and negatives for varying forest buffers is crucial for optimized return on investment. These results can direct these organizations how to best incorporate floodplain restoration and preservation to meet their desired goals while minimizing monetary costs.

Results also show that these stakeholders can expand the land to consider for restoration efforts that was previously limited by suitable flooding duration and frequency conditions. The results indicate that restoration efforts have the potential to create the necessary flooding conditions for floodplain forest suitability. Therefore, stakeholders would not be restricted to lands that already have the necessary flooding duration conditions. Furthermore, because results show that restoration leads to increased flooding extent and duration, there is the additional benefit of providing natural eradication for non-native species that can otherwise be difficult and costly to maintain.

The scenarios addressed in this research investigated LULC changes in the floodplain. Future concerns about flood risk are twofold, with LULC and climate change both impacting how flood events will impact the area. Therefore, projections of potential future flows can be updated in the model to analyze this area of concern, and future analysis can investigate more complex scenarios that change both flood events and LULC. Furthermore, managers and planners will seek case-studies that closely match their local floodplain characteristics, so this methodology for evaluating potential future states of floodplains in the Connecticut River Basin could be expanded to other representative locations within the basin. Finally, this work can be used to provide ecologists and managers with information to better assess, predict, and protect habitat for critical species both currently and into an uncertain future climate.

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Appendices

Appendix A: Model Calibration

The HEC-RAS 2D model was calibrated based of off aerial photographs from two storm events that occurred in April 2011 and March 2010 (Figures A1 and A2). The flooding extent of these events was mapped to satellite imagery and compared to the flooding extent results from the HEC-RAS 2D model. The HEC-RAS 2D model was calibrated by changing the manning's n values in the land cover dataset.

Figure A1: Aerial image derived flooding extent from April 2011 storm event

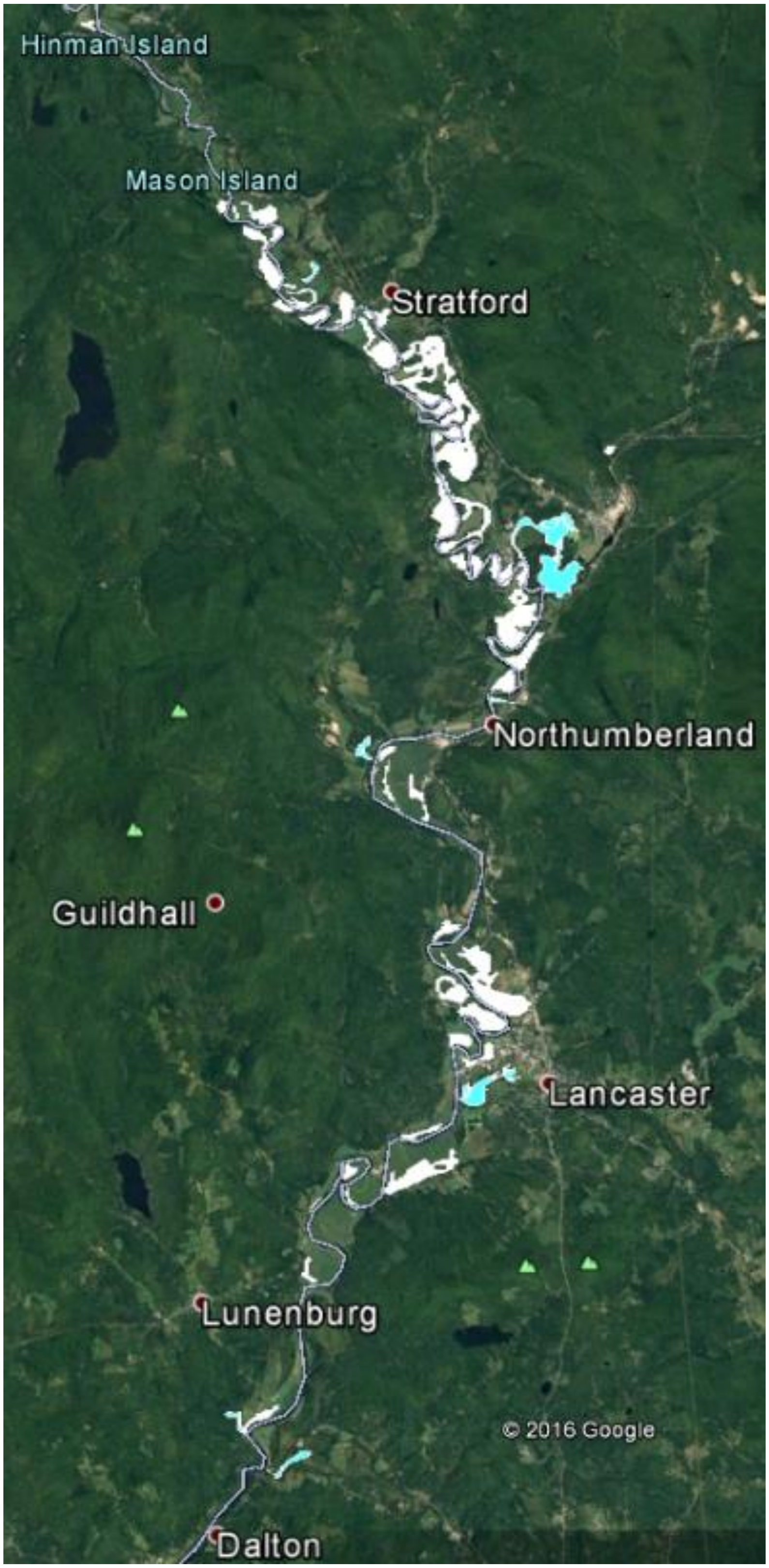
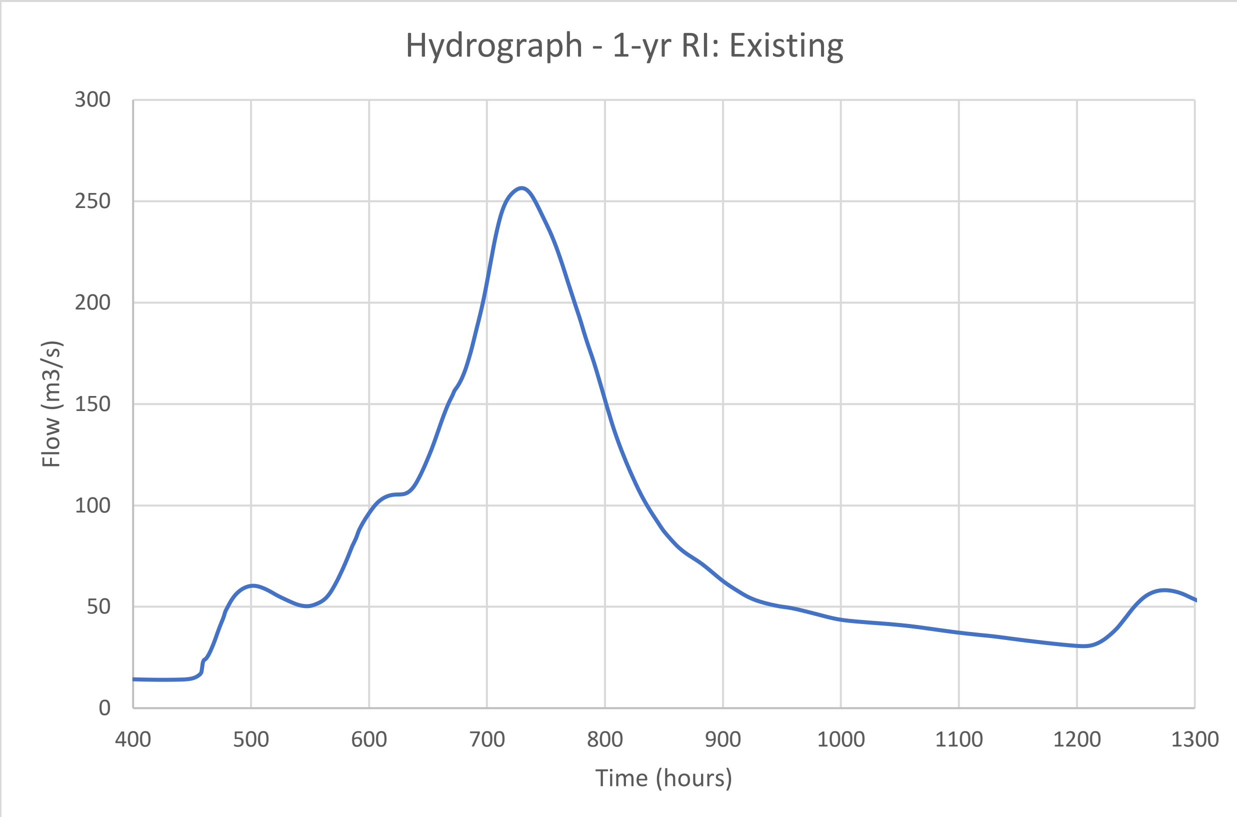
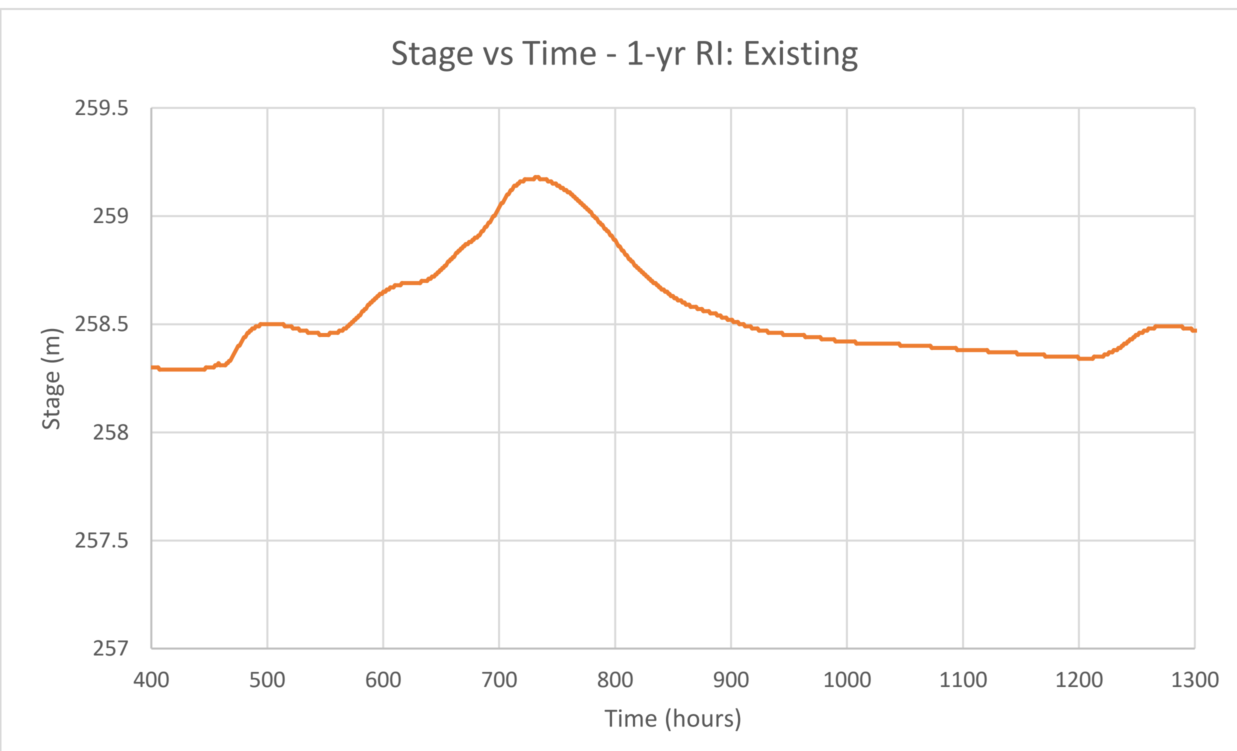


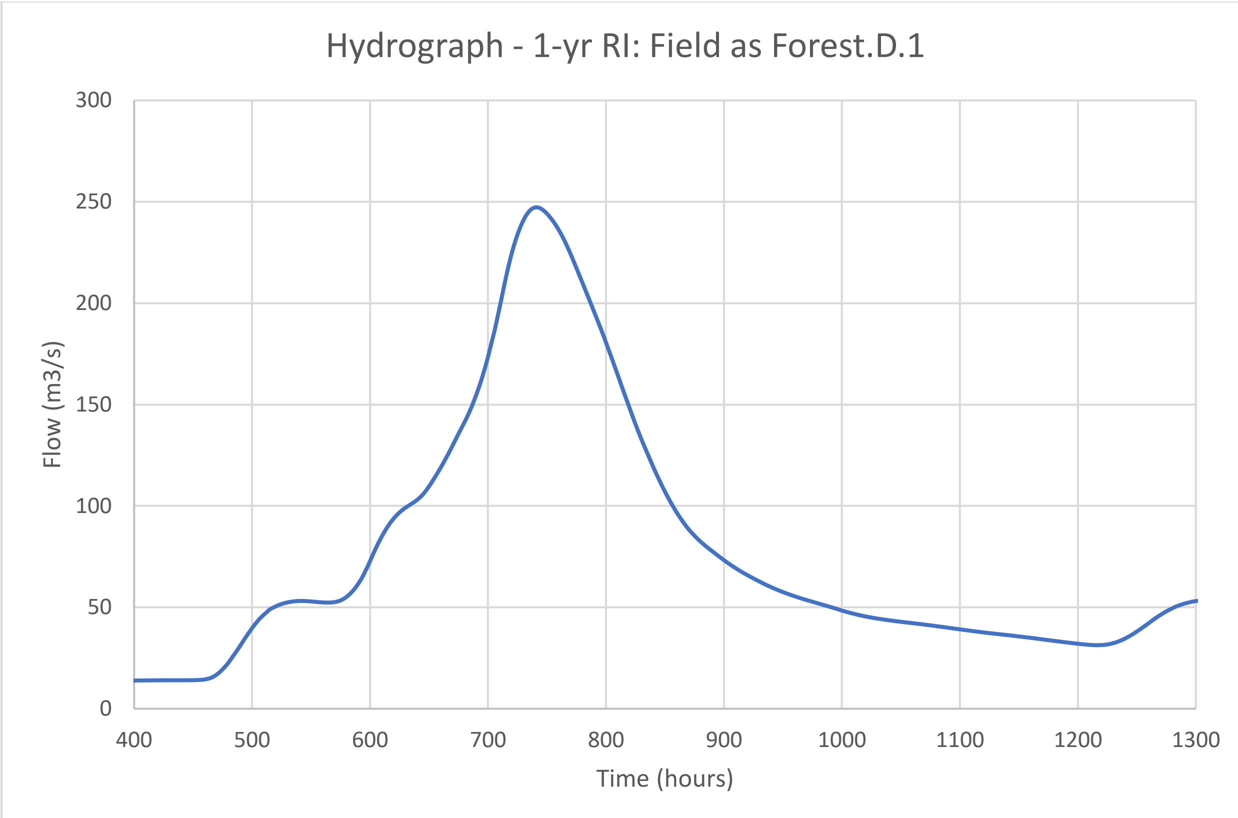
Figure A2: Aerial image derived flooding extent from March 2010 storm event

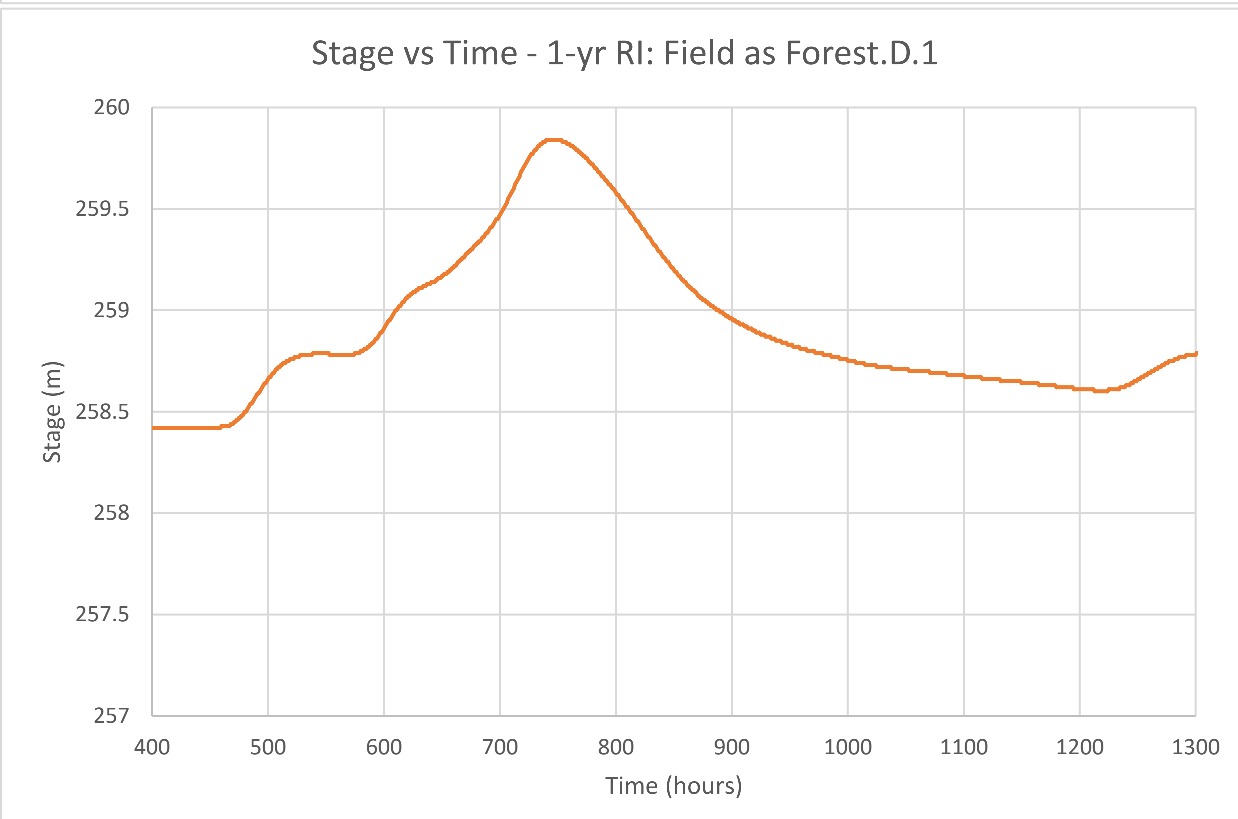
Appendix B

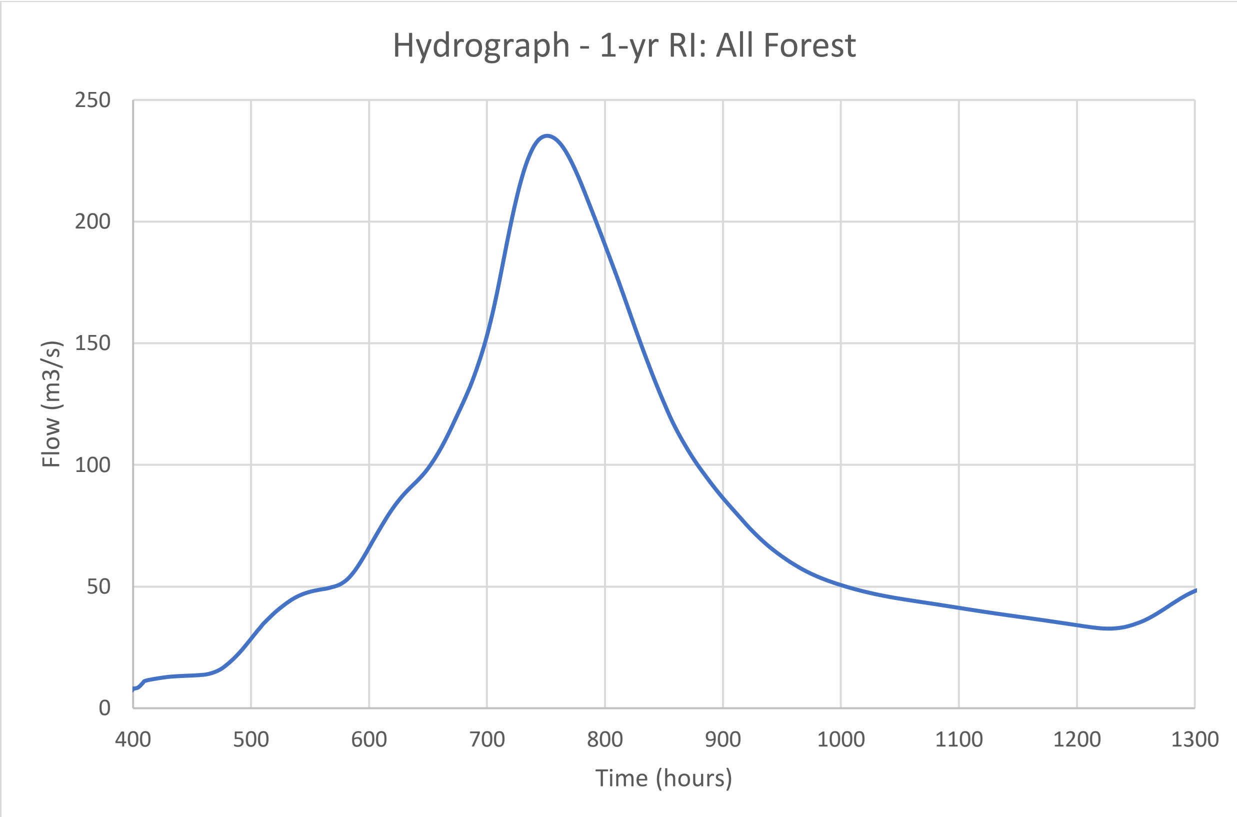
Model results for each scenario



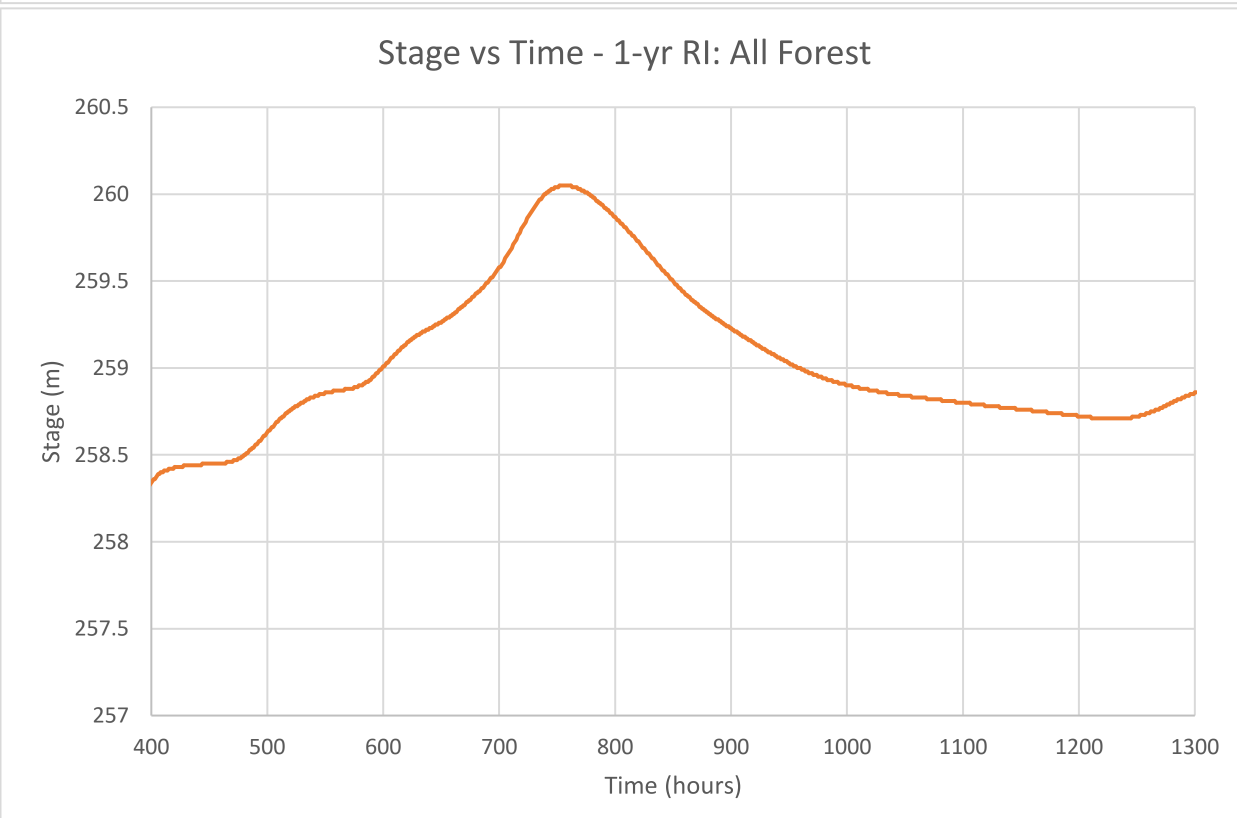



Hydrograph - 1-yr RI: Field as Forest.D.1
Flow (m3/s)
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

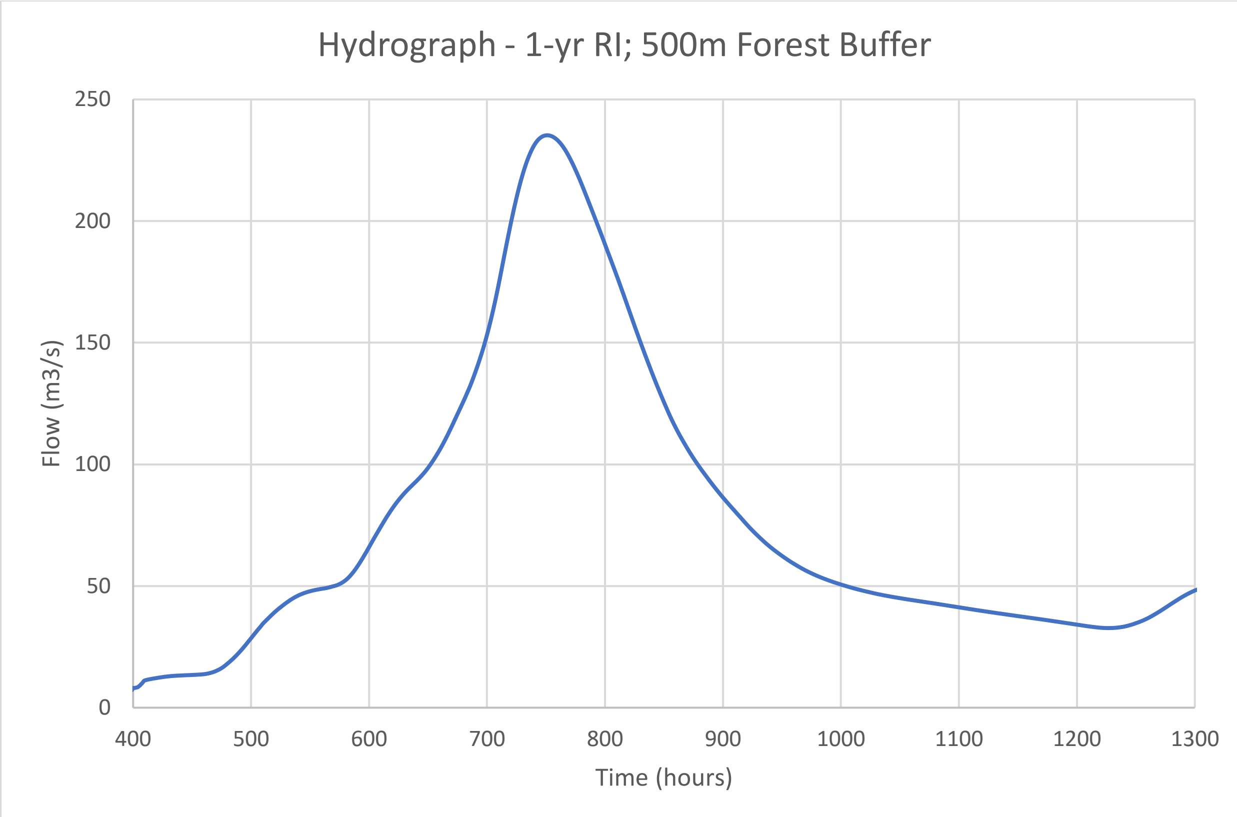

Stage vs Time - 1-yr RI: Field as Forest.D.1
Stage (m)
260
259.5
259
258.5
258
257.5
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)



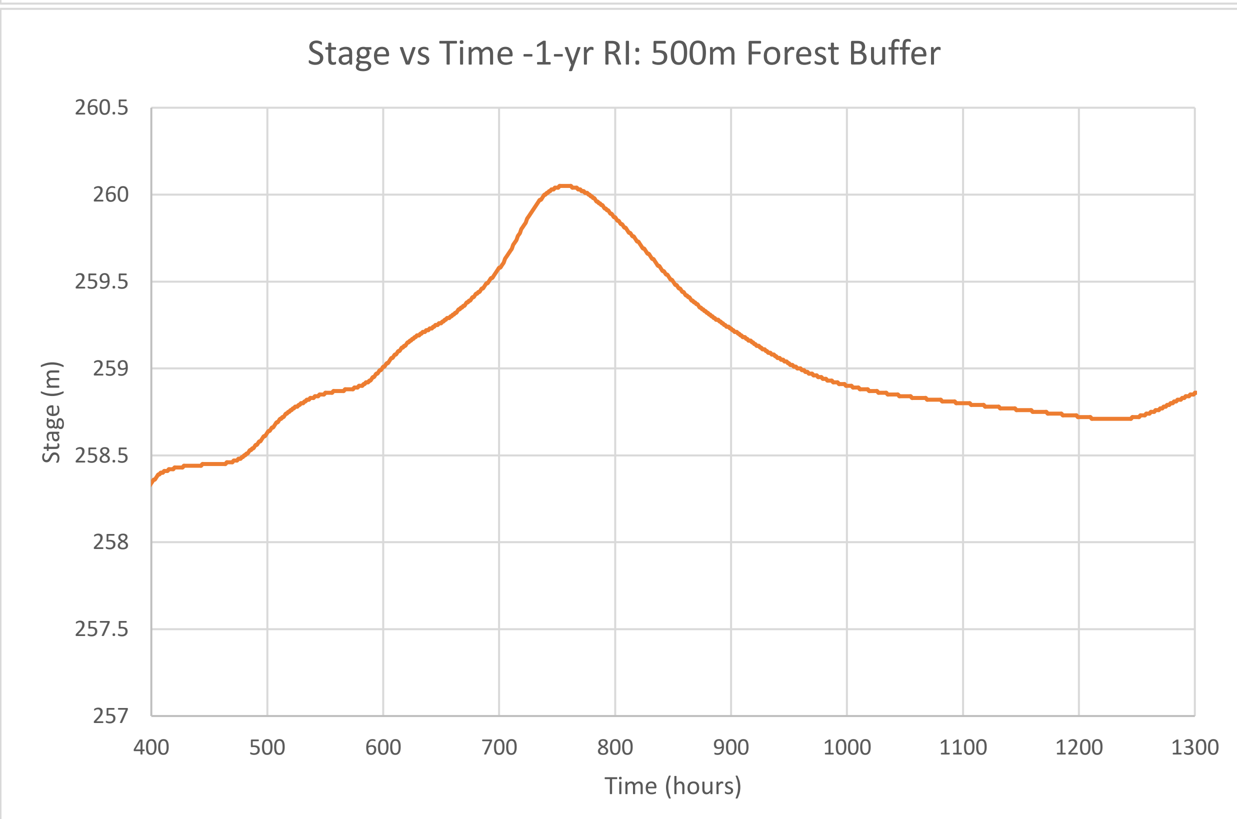
Hydrograph - 1-yr RI: All Forest
Flow (m3/s)
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)



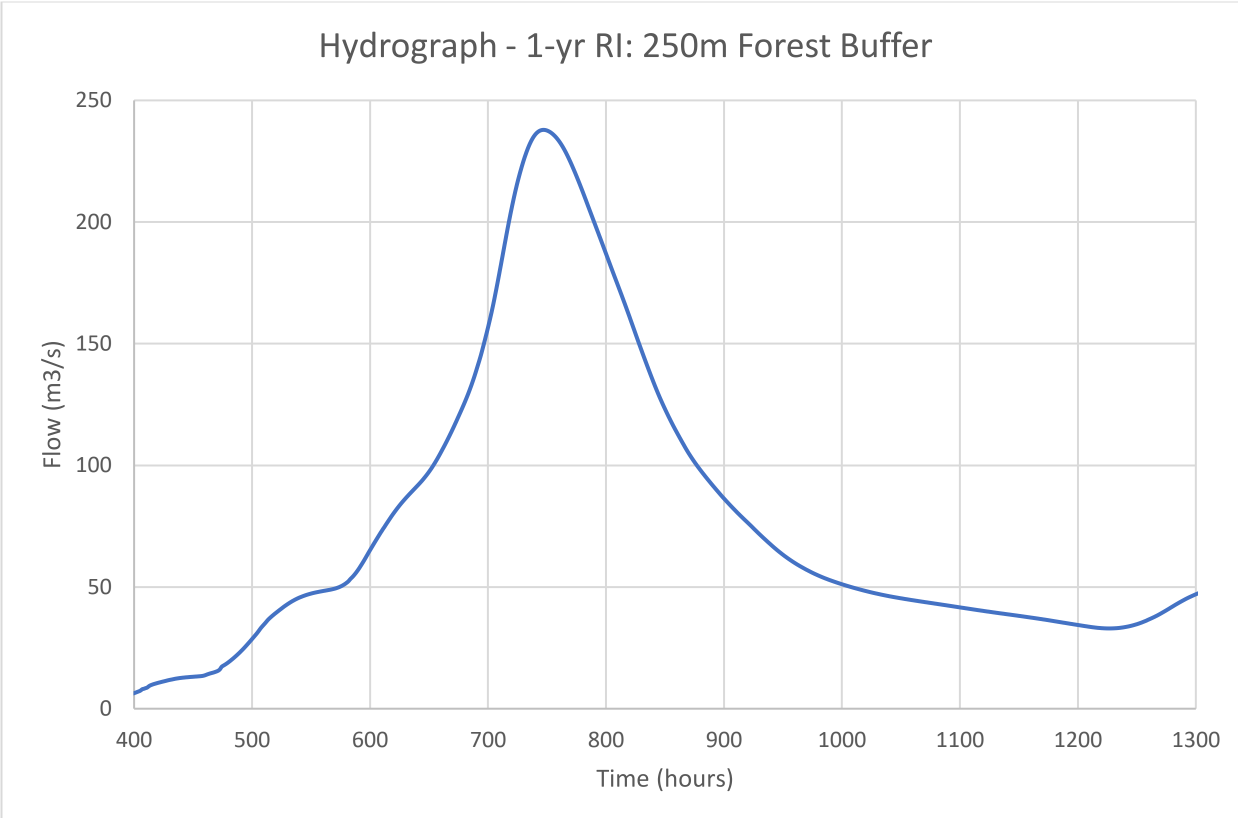
Stage vs Time - 1-yr RI: All Forest
Stage (m)
260.5
260
259.5
259
258.5
258
257.5
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)



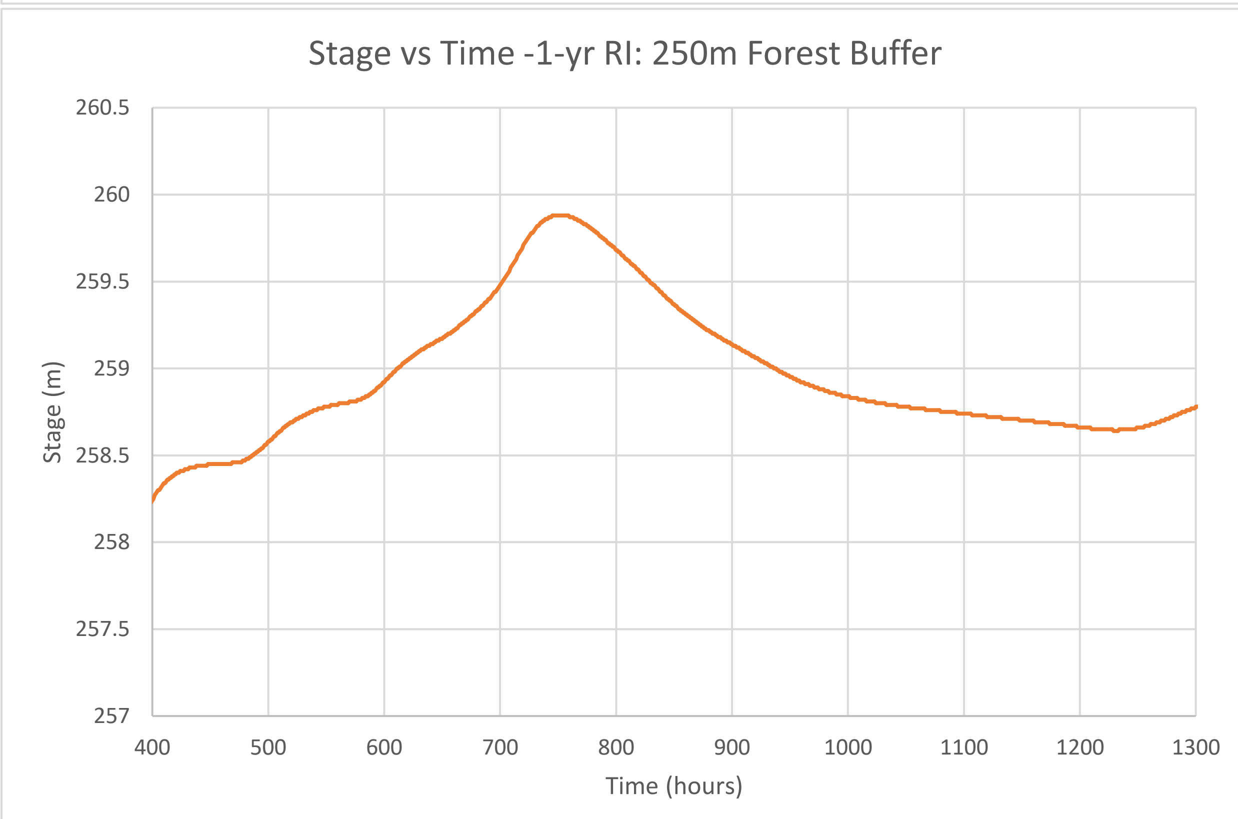
Hydrograph - 1-yr RI; 500m Forest Buffer
Flow (m3/s)
0
50
100
150
200
250
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)



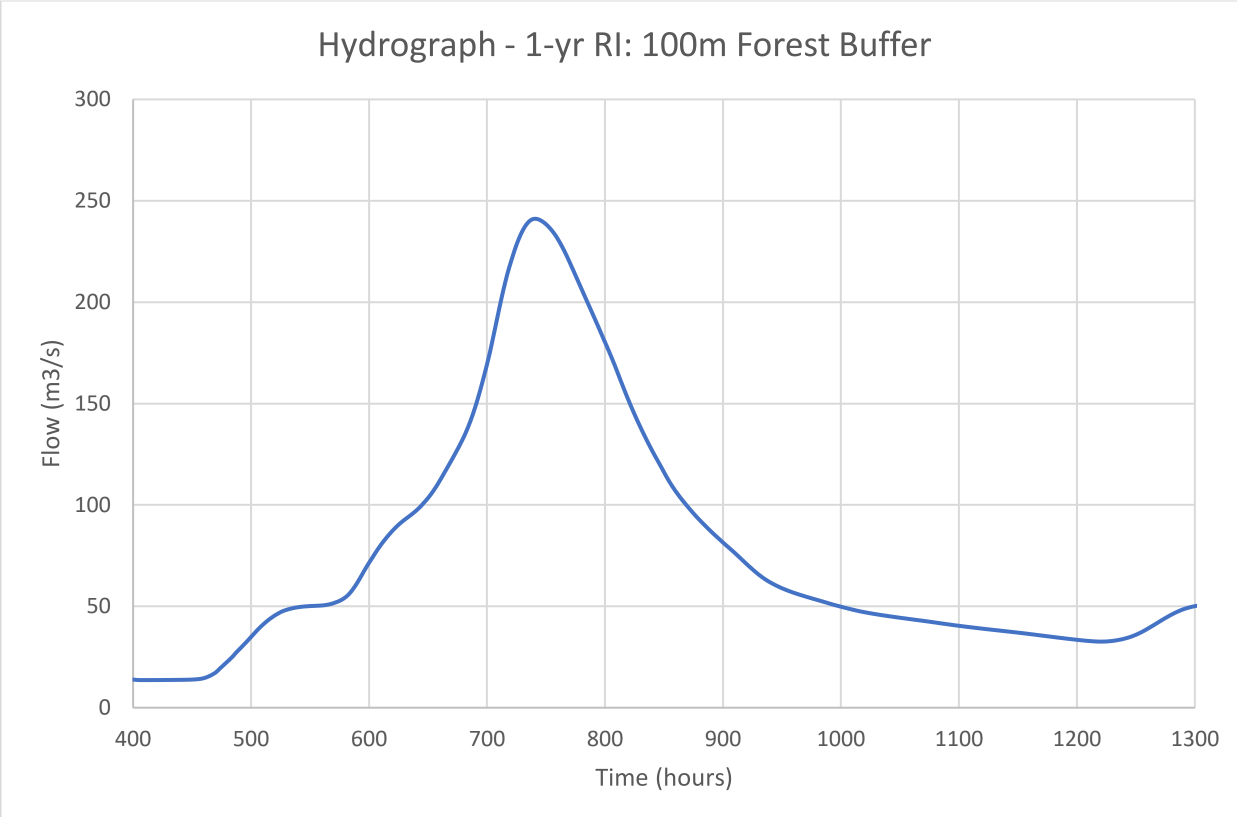
Stage vs Time -1-yr RI: 500m Forest Buffer
Stage (m)
257
257.5
258
258.5
259
259.5
260
260.5
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

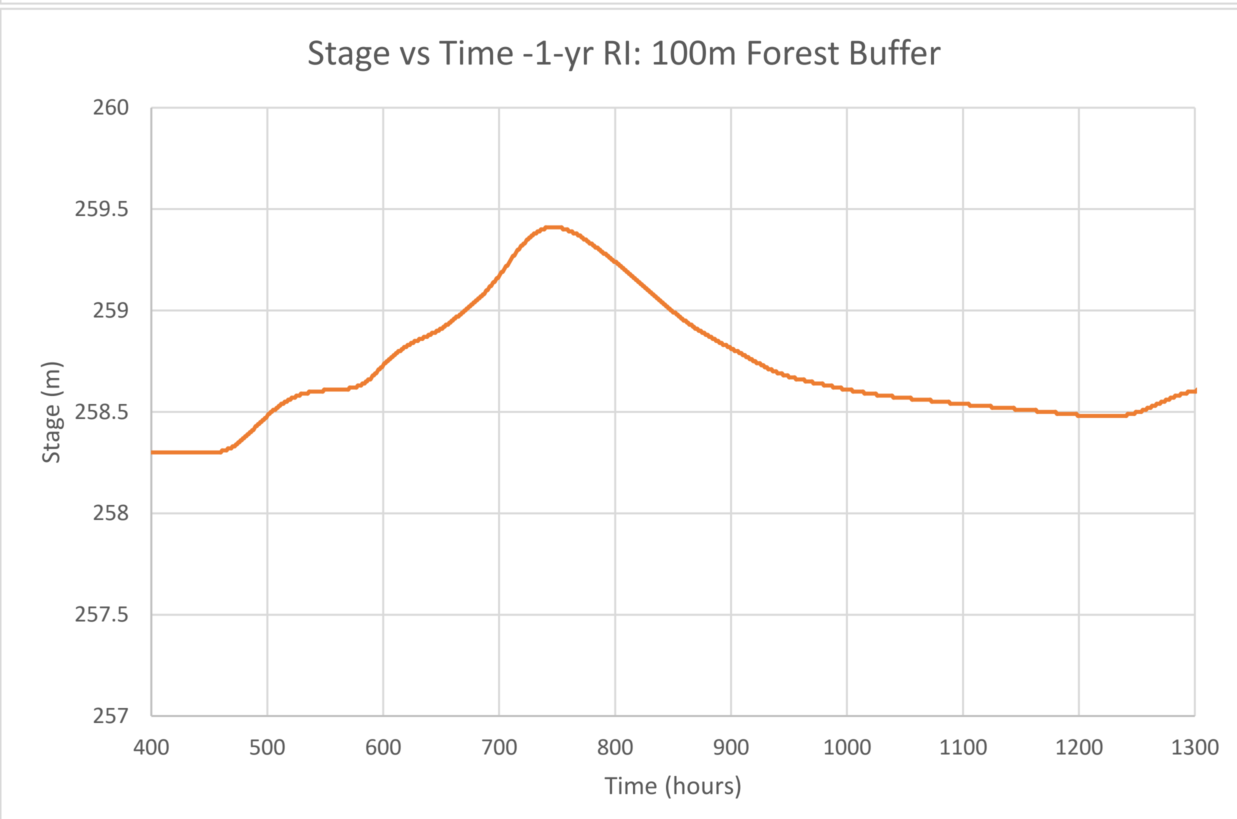


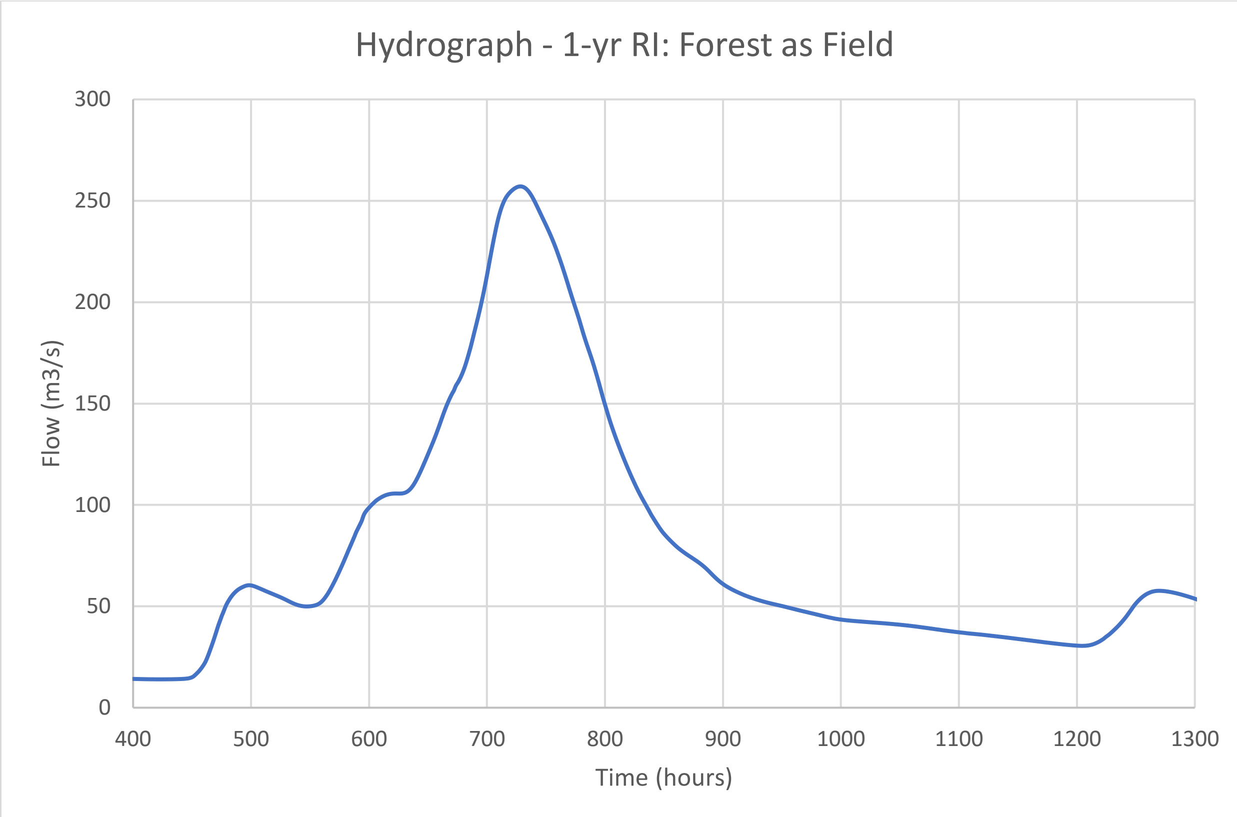
Hydrograph - 1-yr RI: 250m Forest Buffer
Flow (m3/s)
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

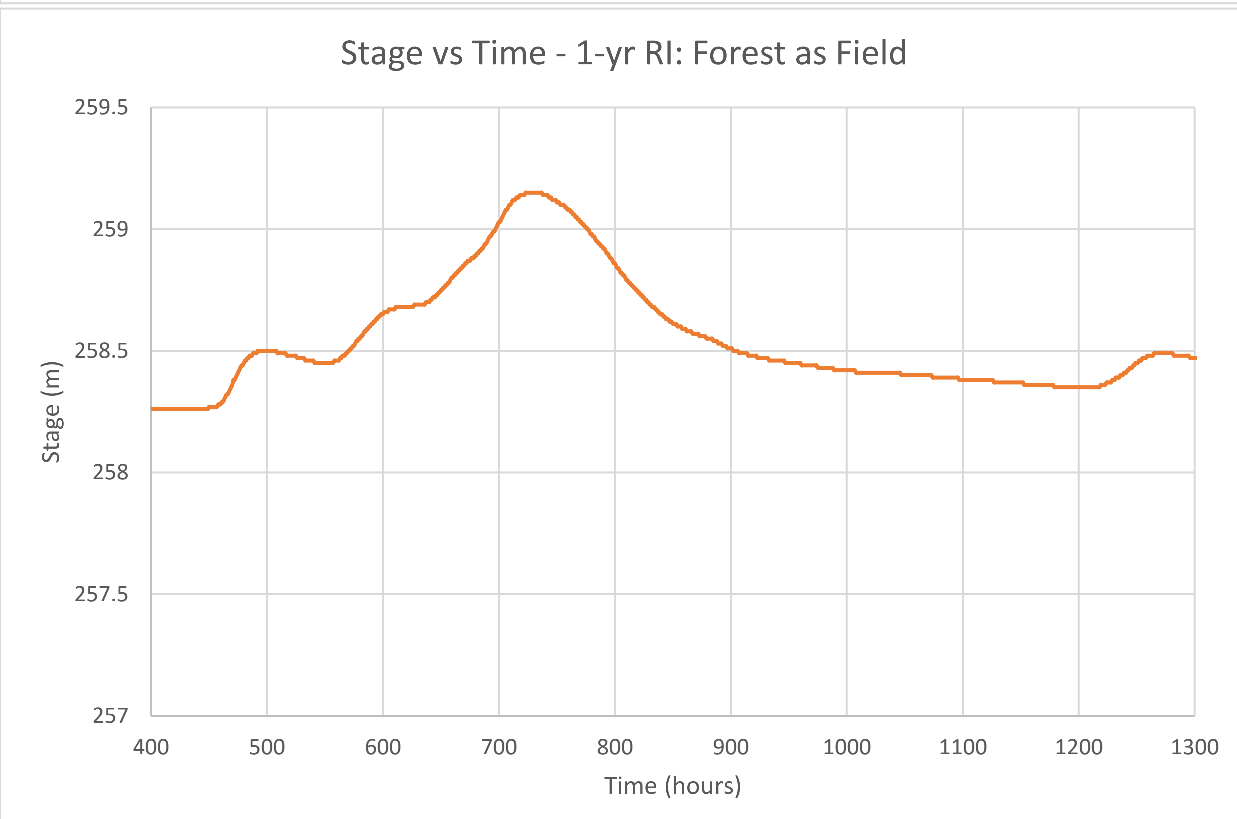


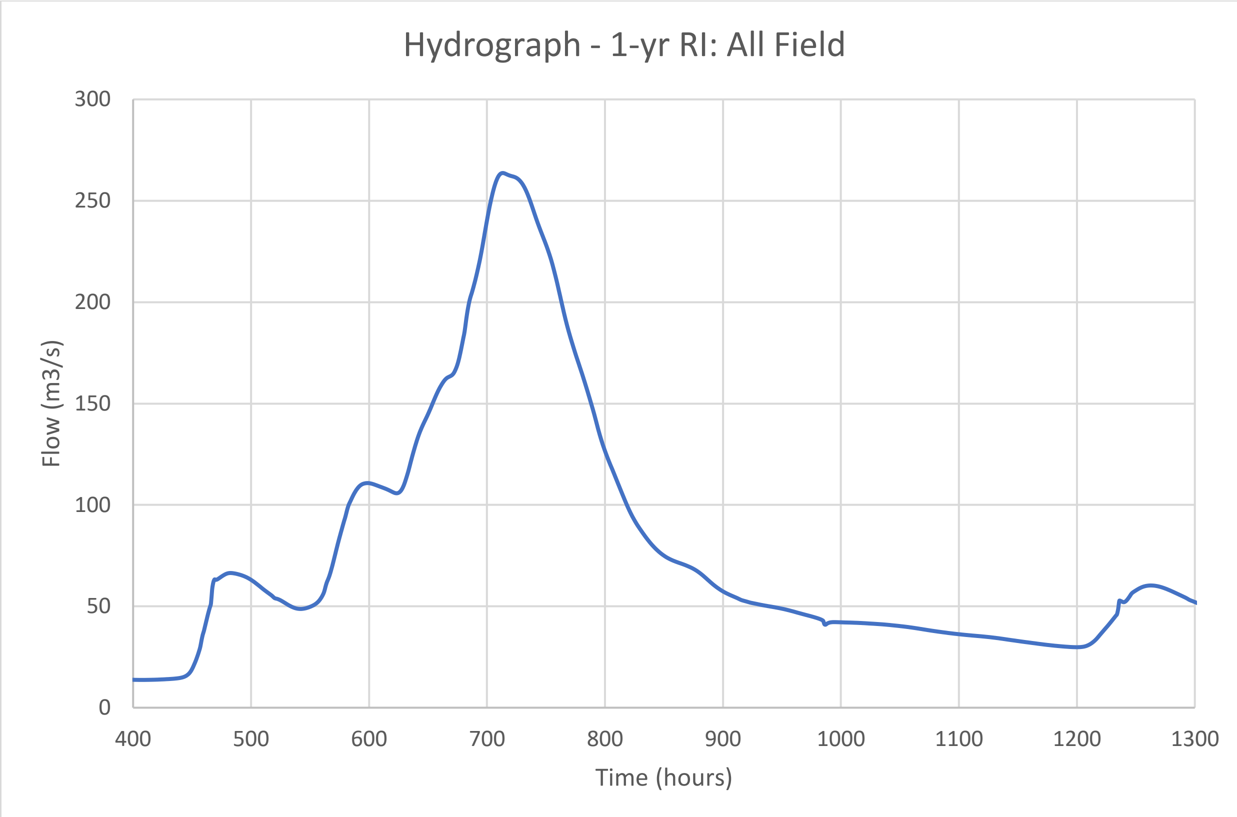
Stage vs Time -1-yr RI: 250m Forest Buffer
Stage (m)
260.5
260
259.5
259
258.5
258
257.5
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

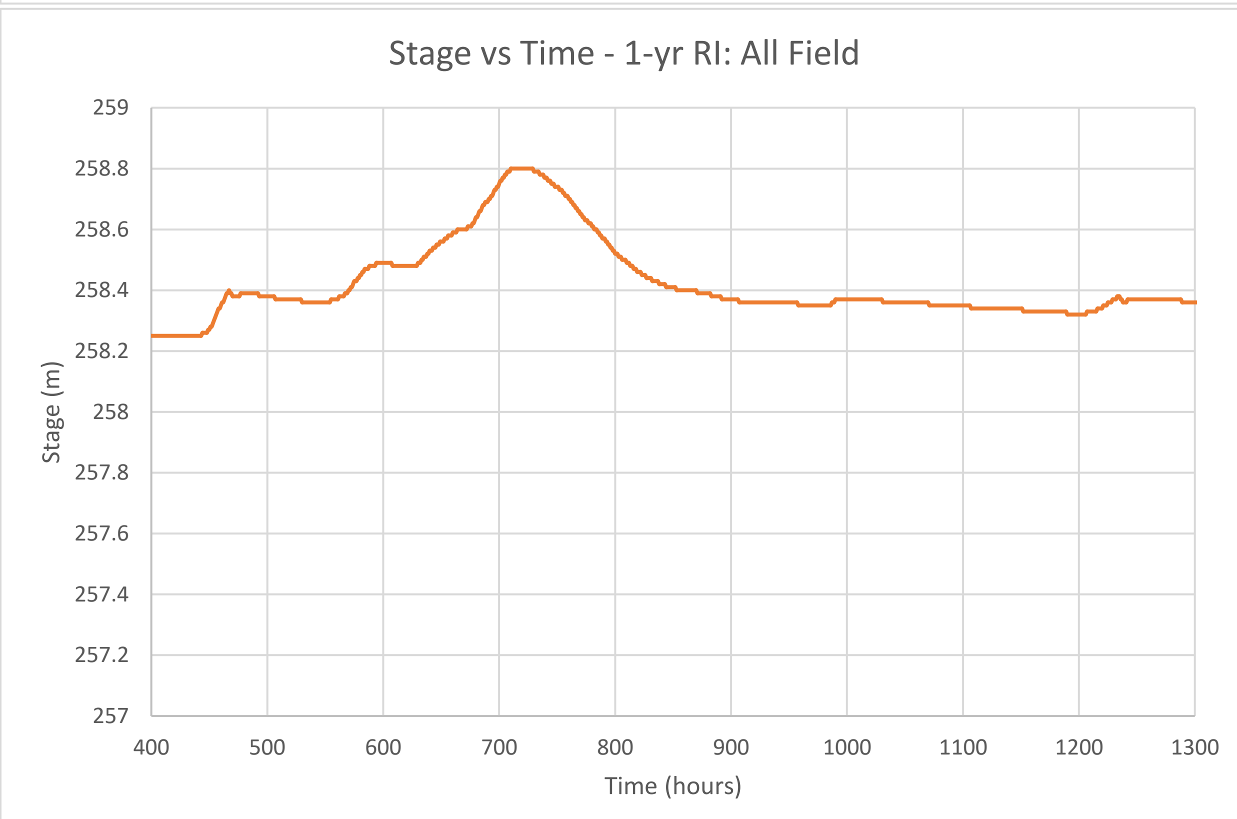

Hydrograph - 1-yr RI: 100m Forest Buffer
300
250
200
150
100
50
0
Flow (m3/s)
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

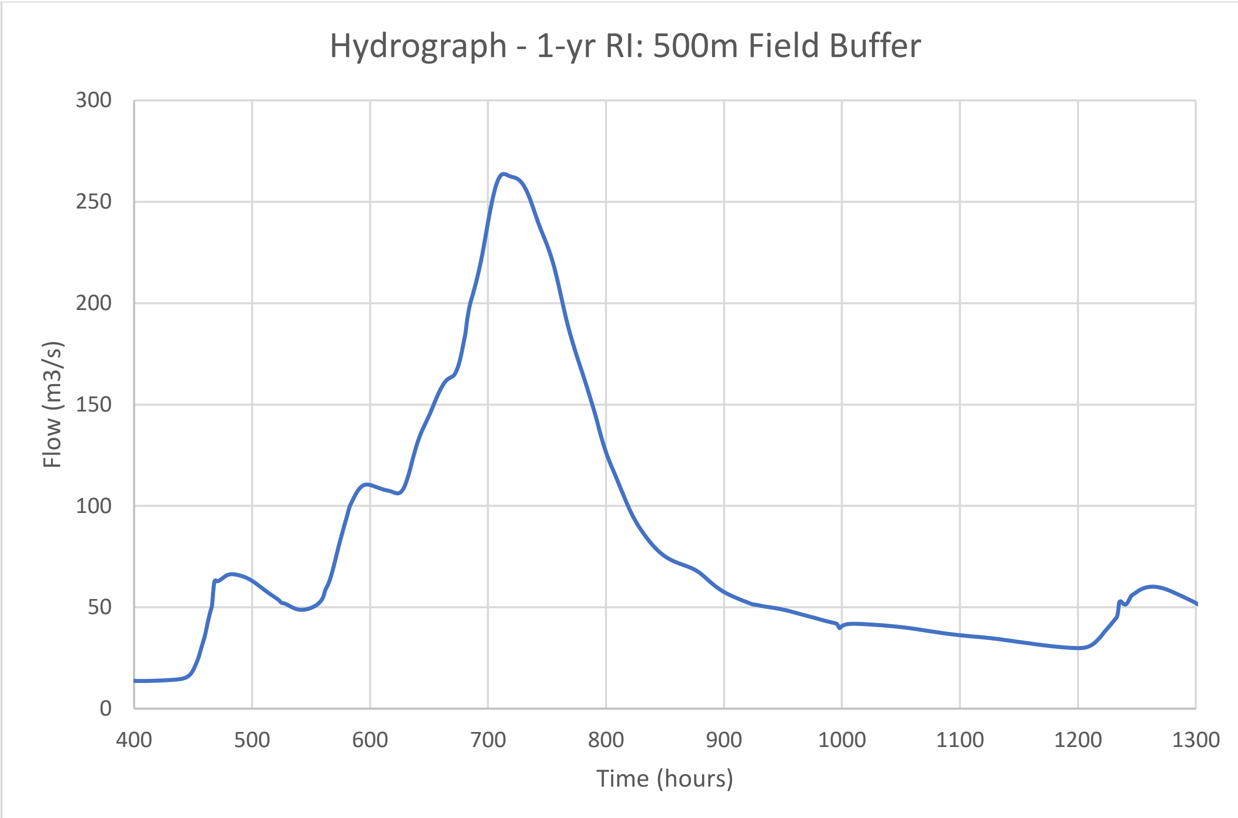

Stage vs Time -1-yr RI: 100m Forest Buffer
260
259.5
259
258.5
258
257.5
257
Stage (m)
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)


Hydrograph - 1-yr RI: Forest as Field
Flow (m3/s)
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

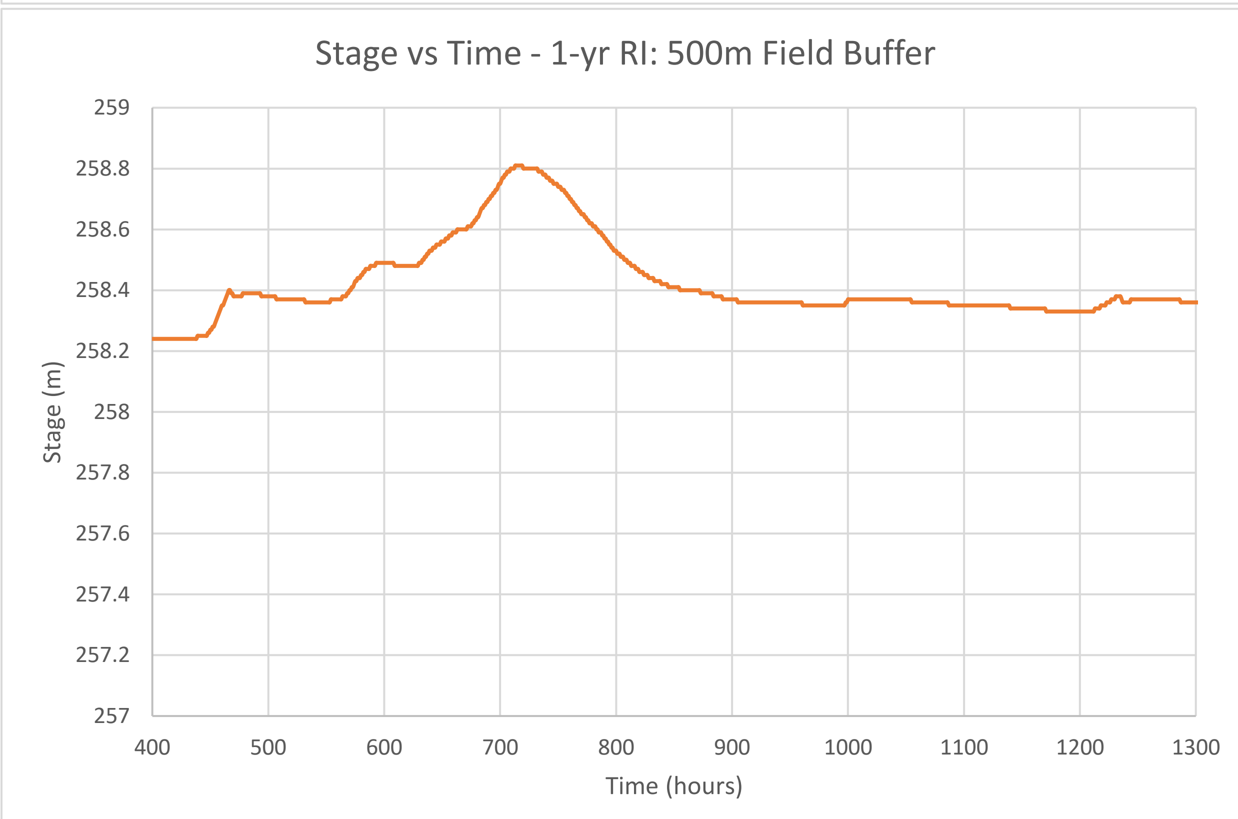

Stage vs Time - 1-yr RI: Forest as Field
Stage (m)
259.5
259
258.5
258
257.5
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)


Hydrograph - 1-yr RI: All Field
Flow (m3/s)
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

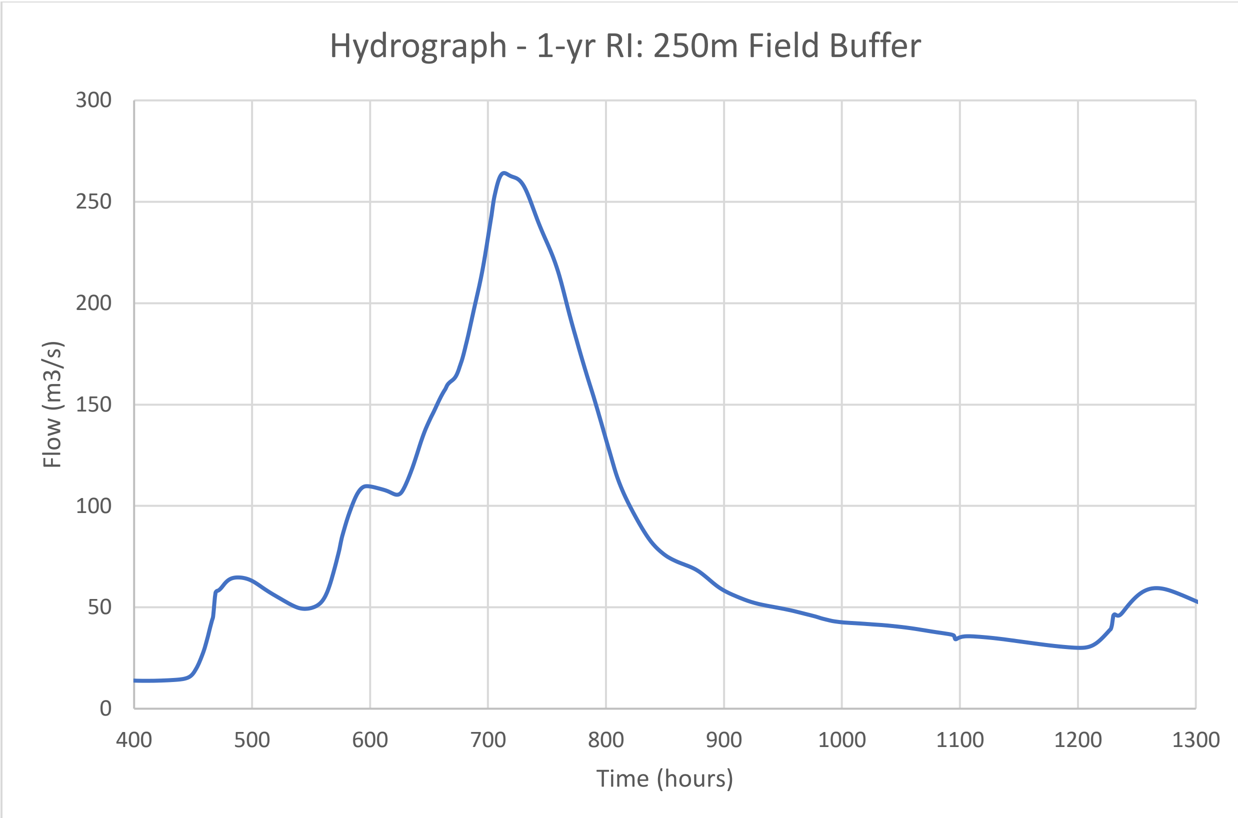

Stage vs Time - 1-yr RI: All Field
Stage (m)
259
258.8
258.6
258.4
258.2
258
257.8
257.6
257.4
257.2
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

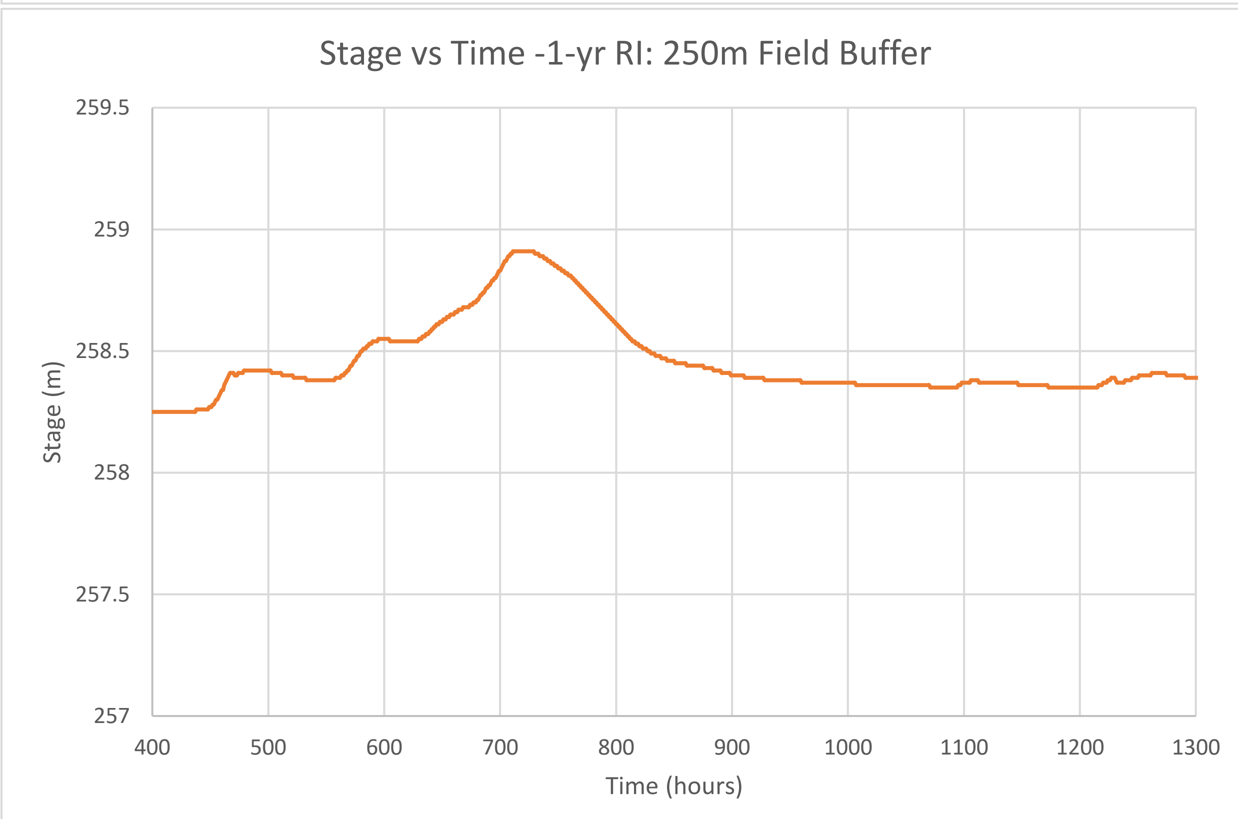


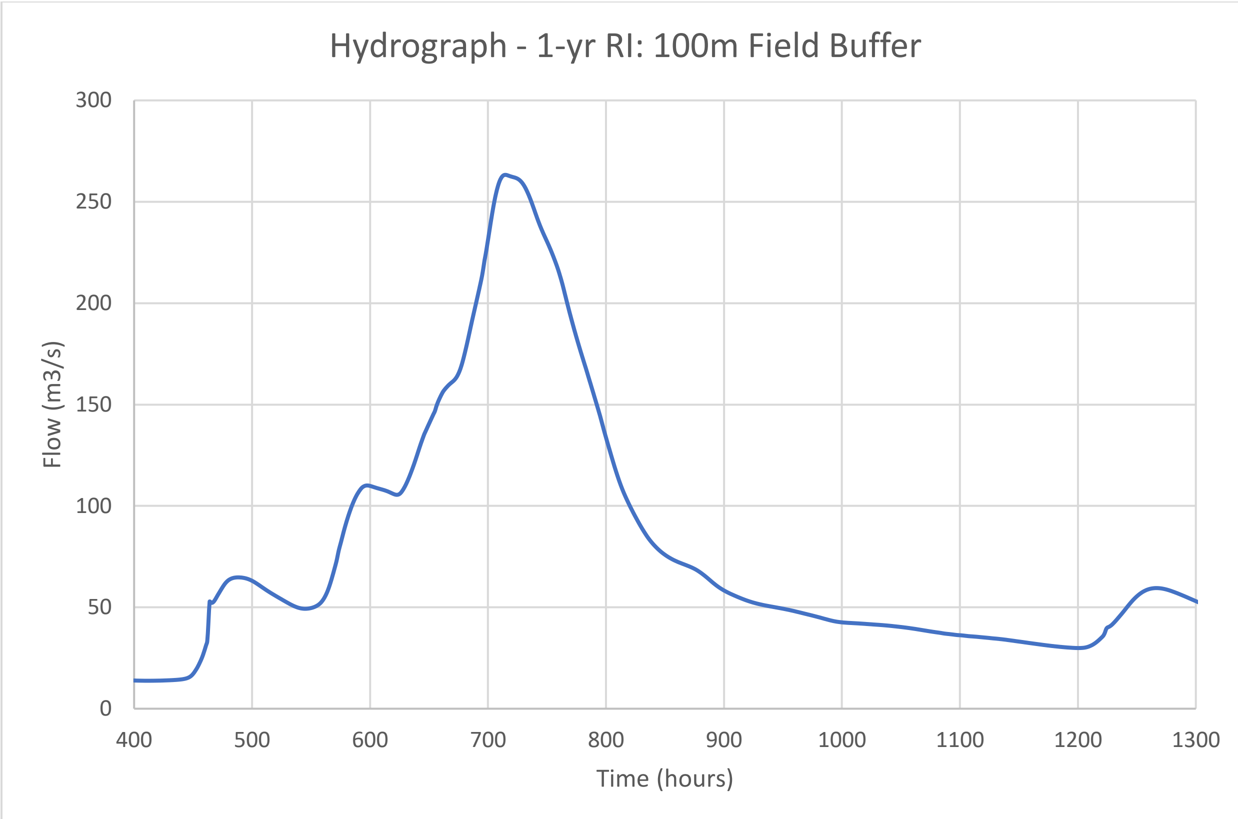
Hydrograph - 1-yr RI: 500m Field Buffer
Flow (m3/s)
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

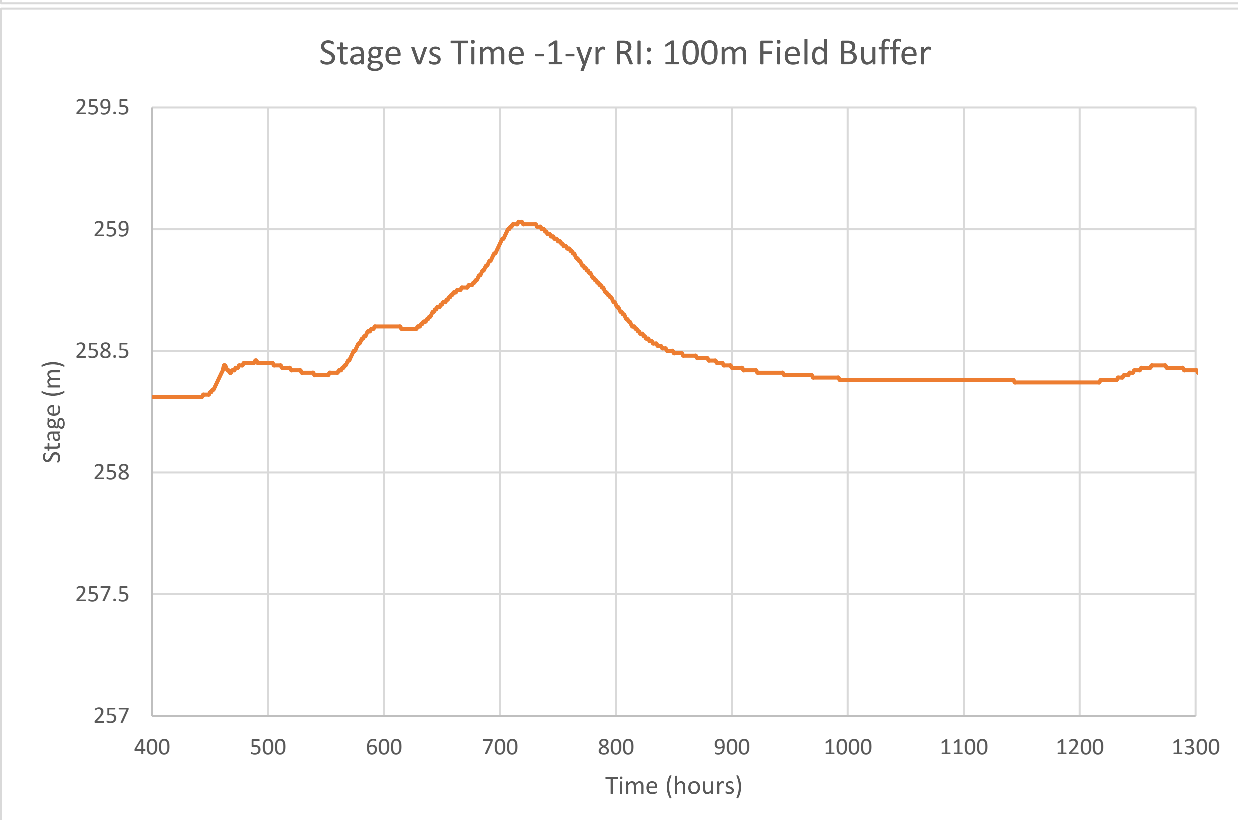


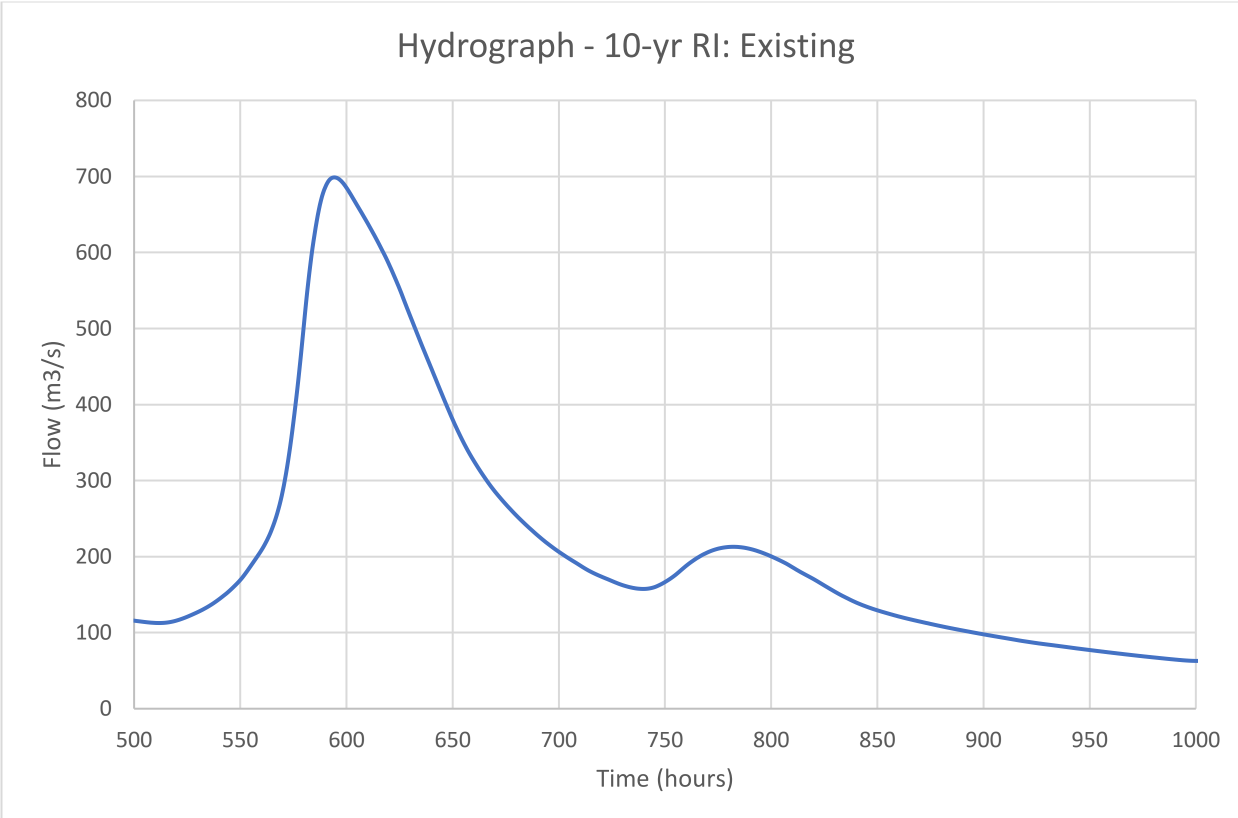
Stage vs Time - 1-yr RI: 500m Field Buffer
Stage (m)
259
258.8
258.6
258.4
258.2
258
257.8
257.6
257.4
257.2
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

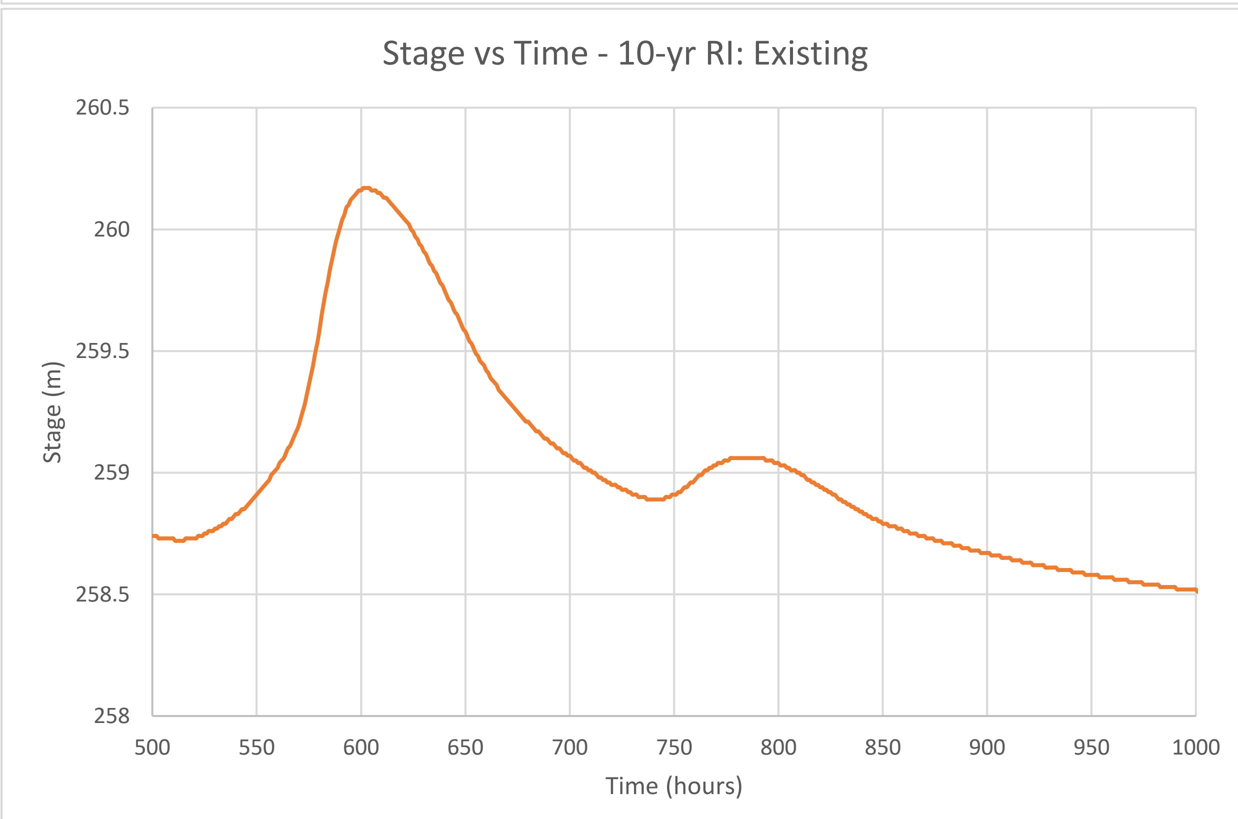

Hydrograph - 1-yr RI: 250m Field Buffer
Flow (m3/s)
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

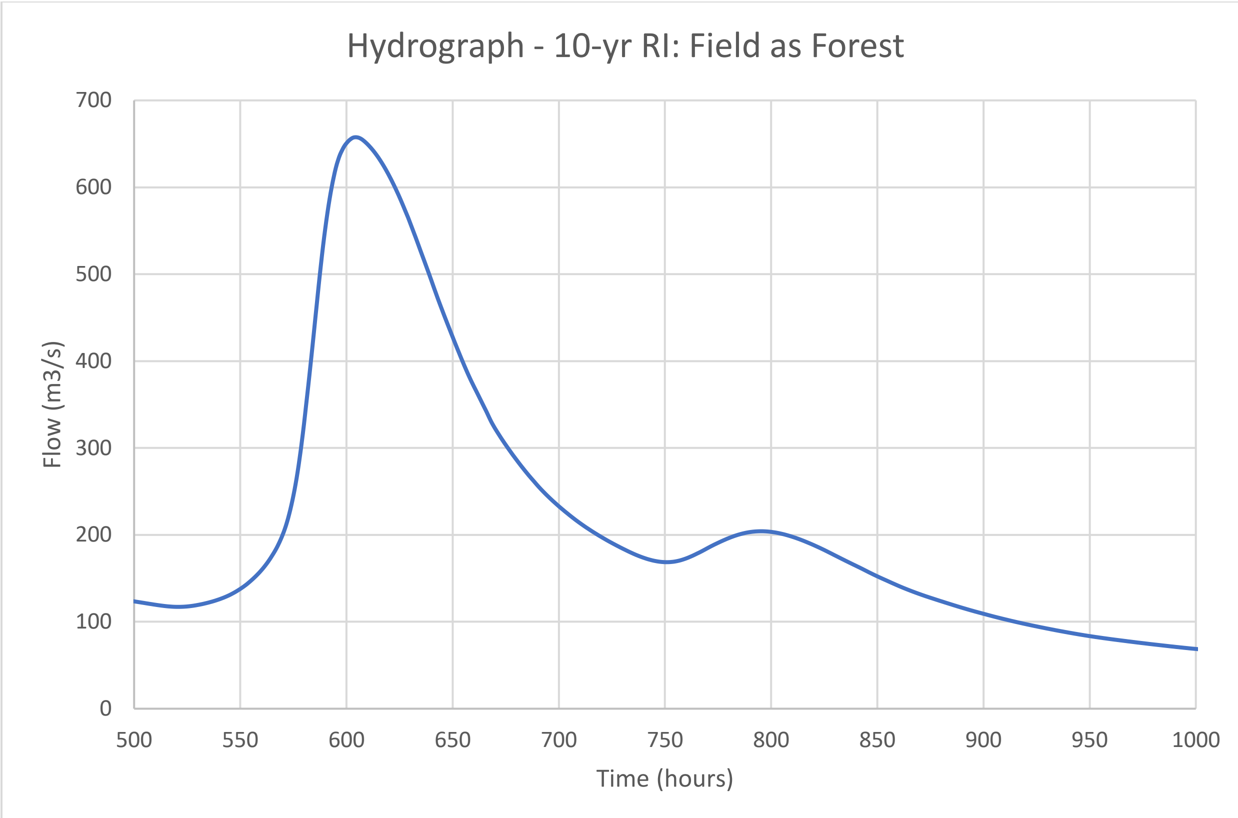

Stage vs Time -1-yr RI: 250m Field Buffer
Stage (m)
259.5
259
258.5
258
257.5
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

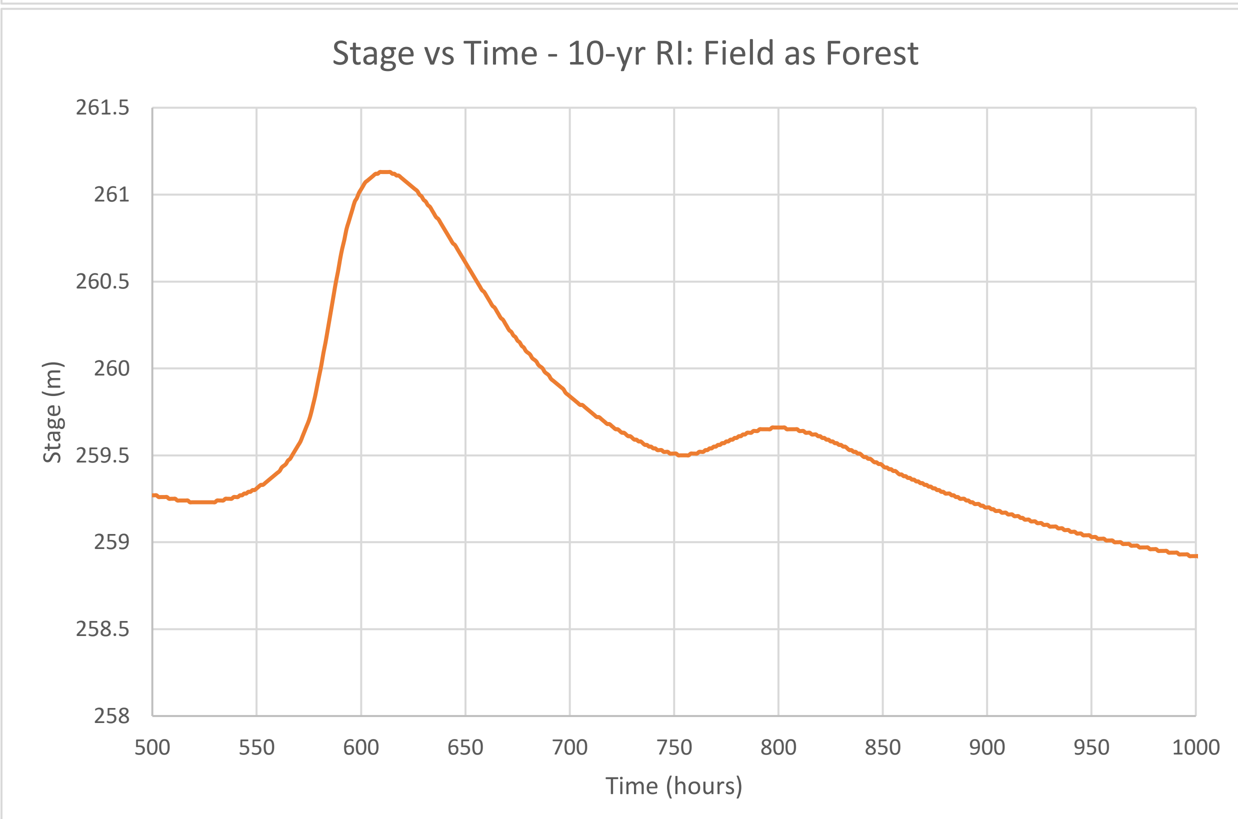

Hydrograph - 1-yr RI: 100m Field Buffer
Flow (m3/s)
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)

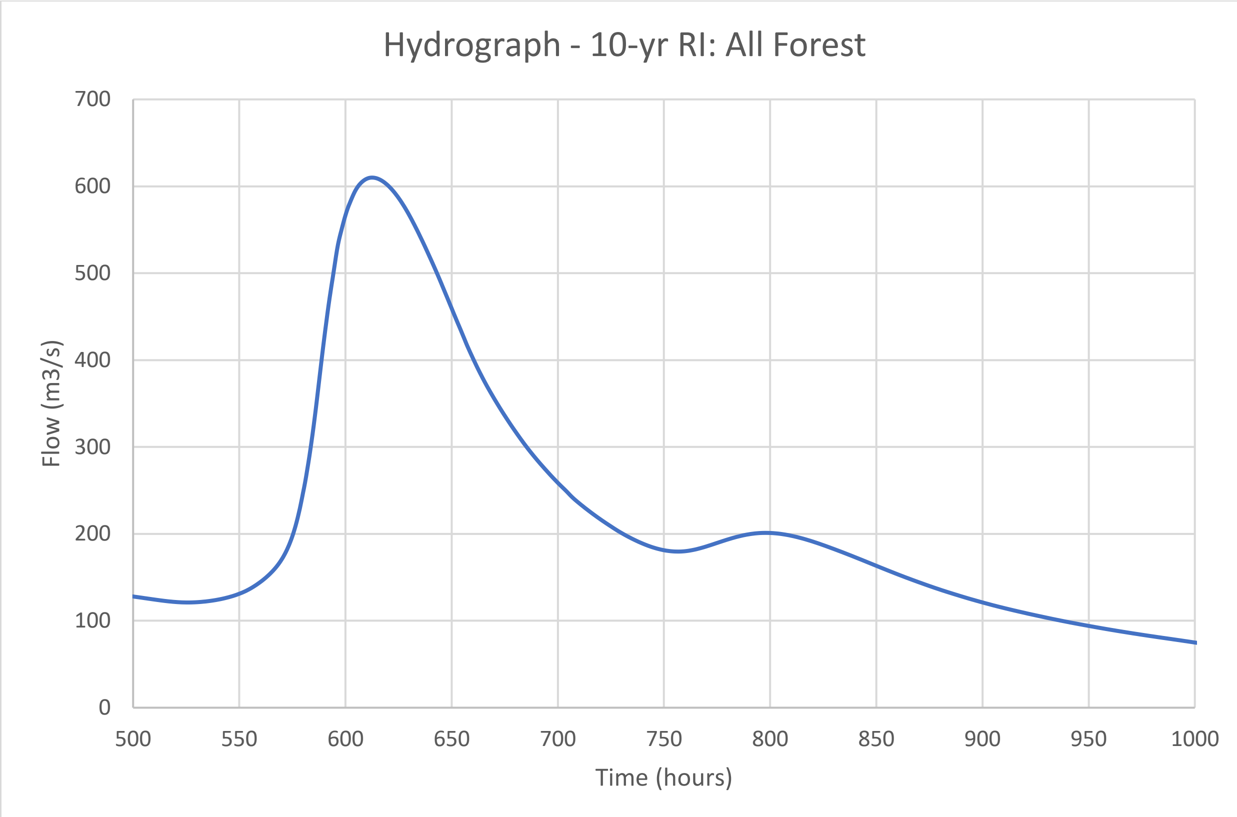

Stage vs Time -1-yr RI: 100m Field Buffer
Stage (m)
259.5
259
258.5
258
257.5
257
400
500
600
700
800
900
1000
1100
1200
1300
Time (hours)


Hydrograph - 10-yr RI: Existing
Flow (m3/s)
800
700
600
500
400
300
200
100
0
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

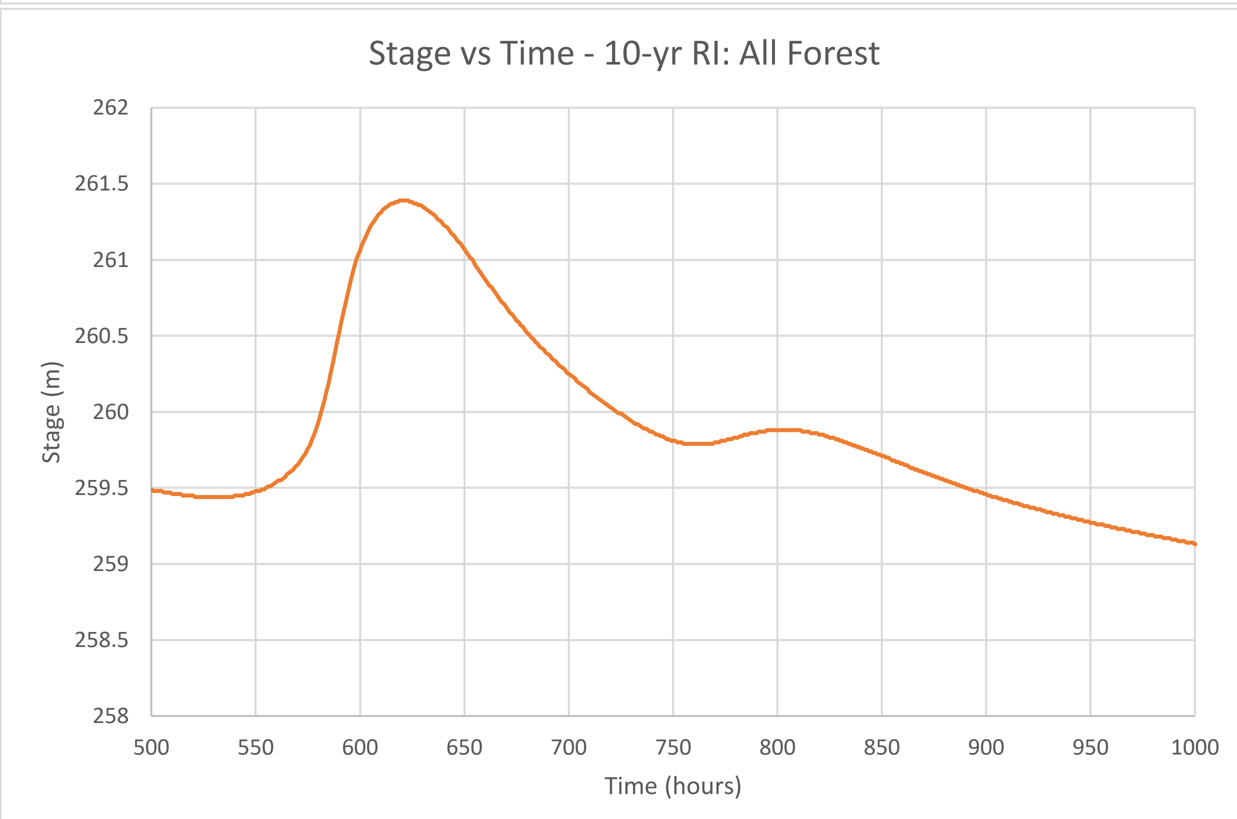

Stage vs Time - 10-yr RI: Existing
Stage (m)
260.5
260
259.5
259
258.5
258
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)


Hydrograph - 10-yr RI: Field as Forest
Flow (m3/s)
0
100
200
300
400
500
600
700
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

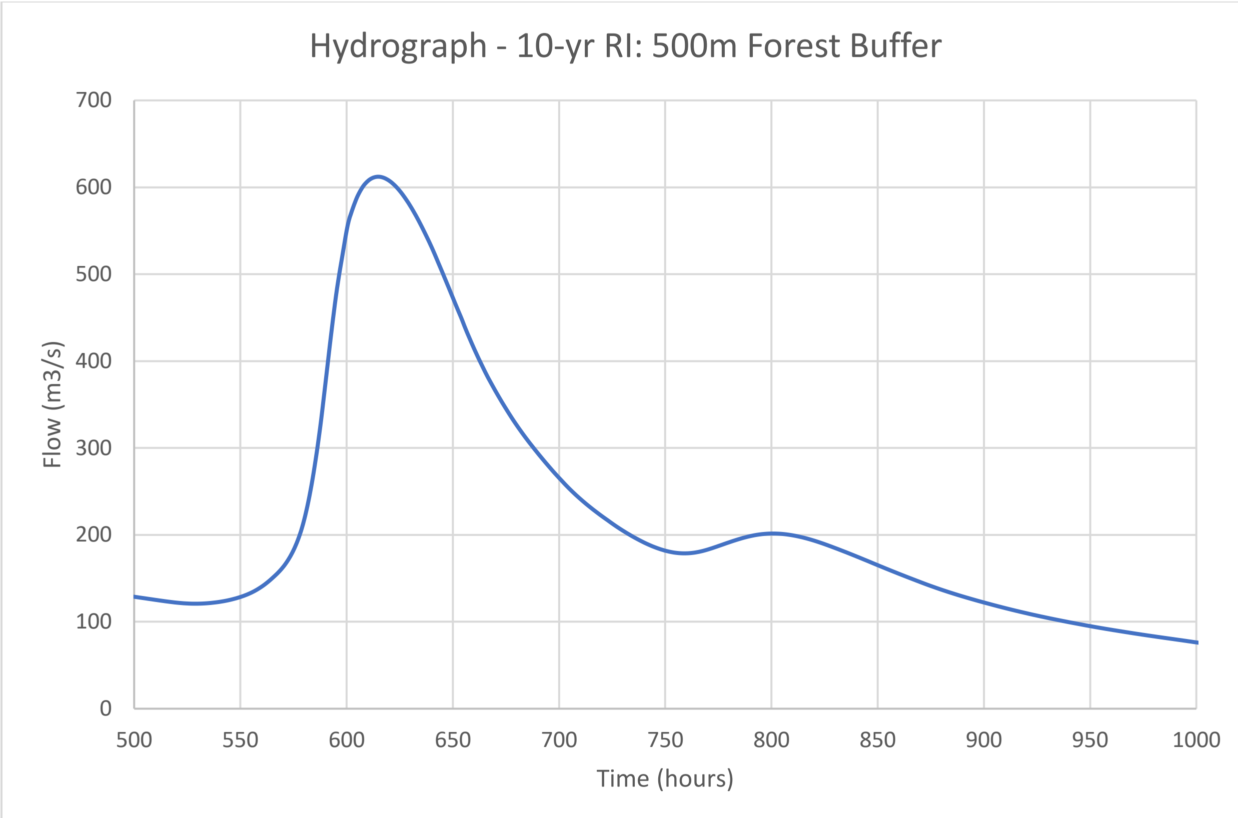

Stage vs Time - 10-yr RI: Field as Forest
Stage (m)
258
258.5
259
259.5
260
260.5
261
261.5
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)



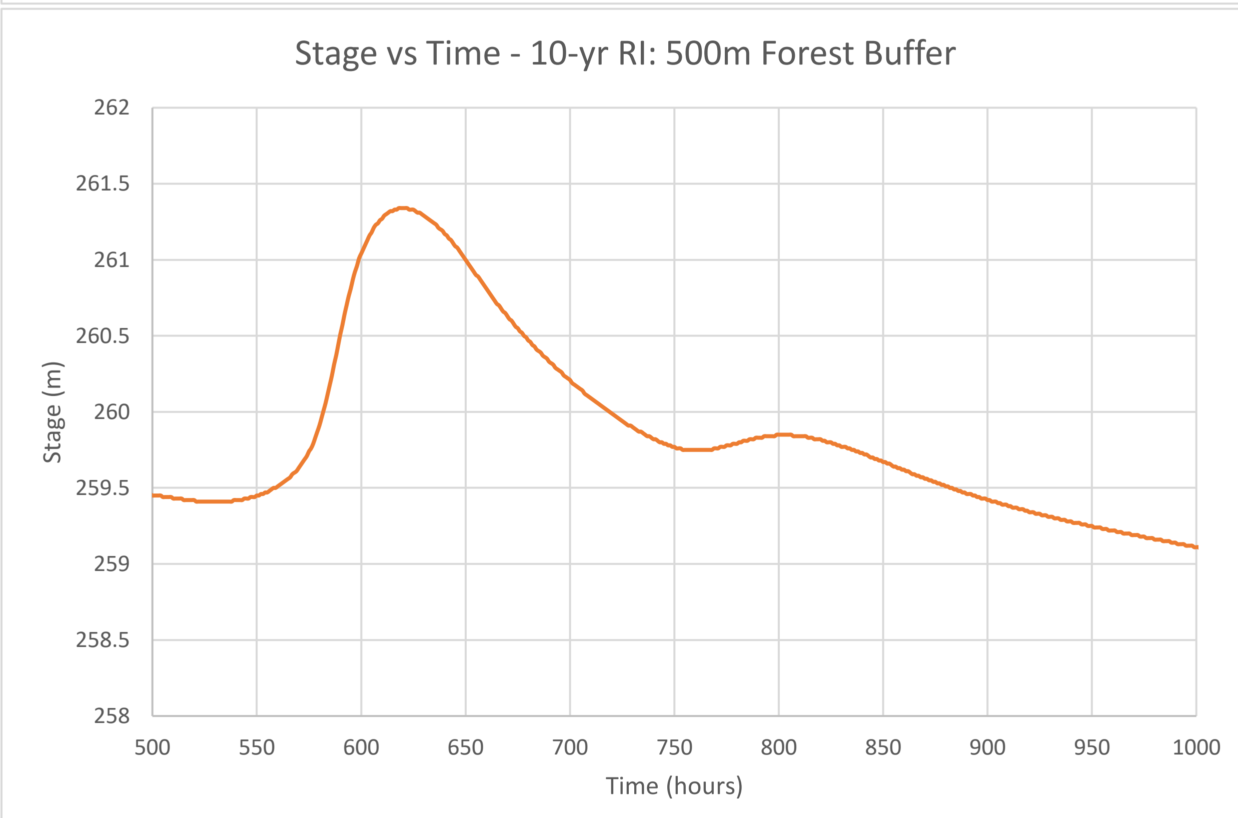
Hydrograph - 10-yr RI: All Forest
Flow (m3/s)
0
100
200
300
400
500
600
700
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)



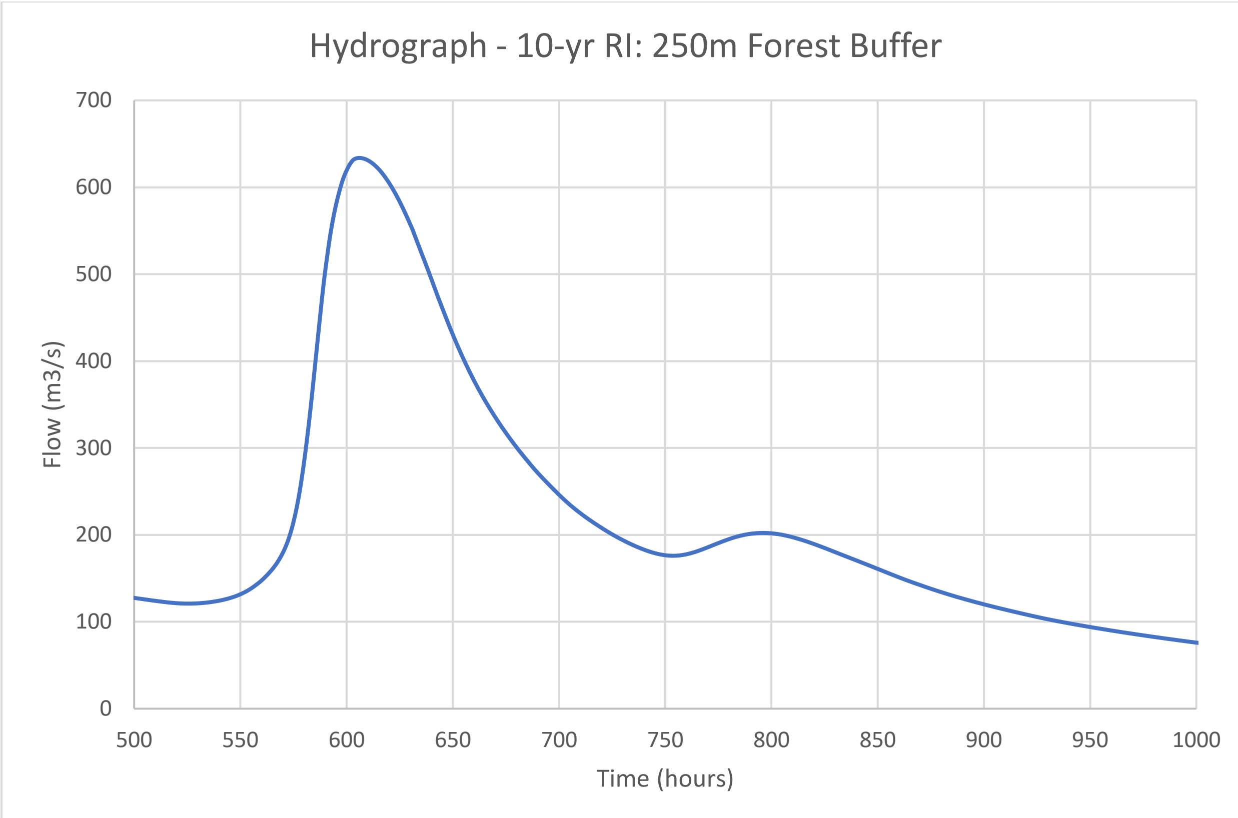
Stage vs Time - 10-yr RI: All Forest
Stage (m)
258
258.5
259
259.5
260
260.5
261
261.5
262
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

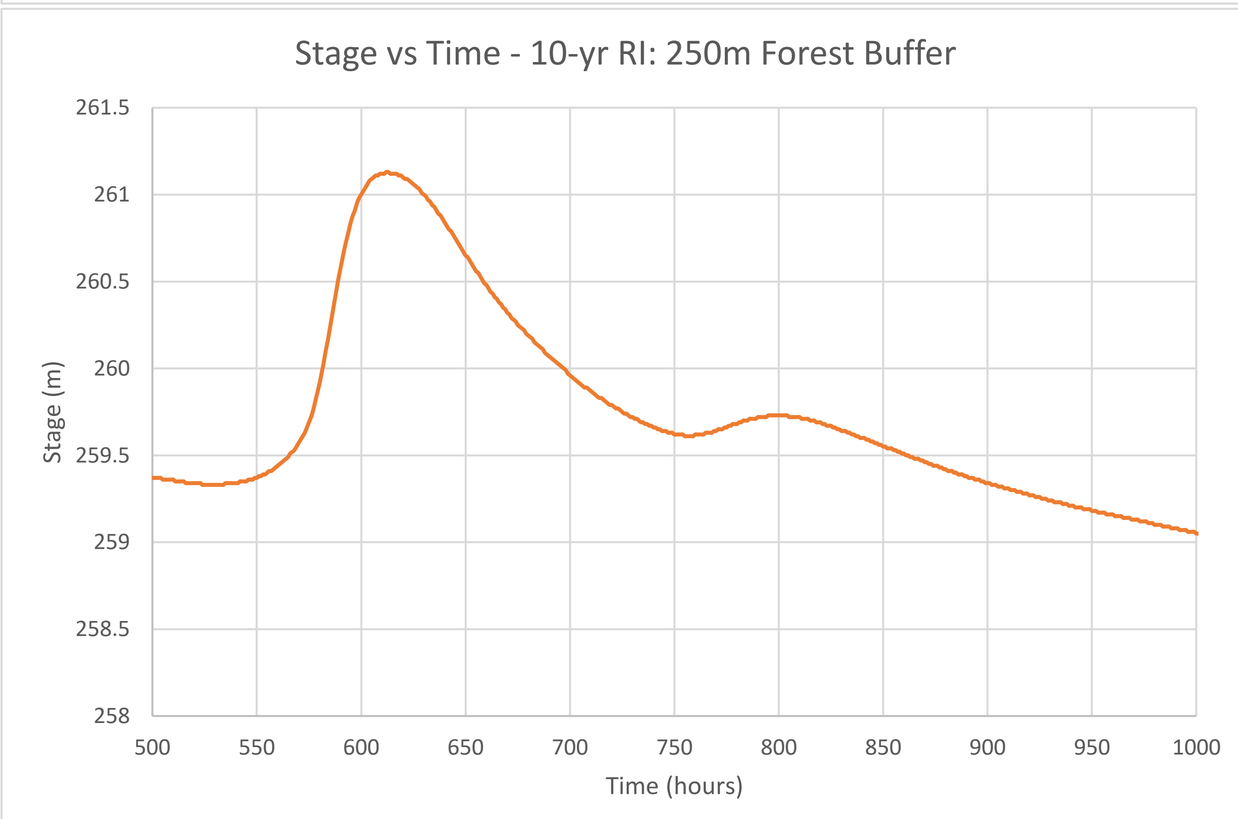


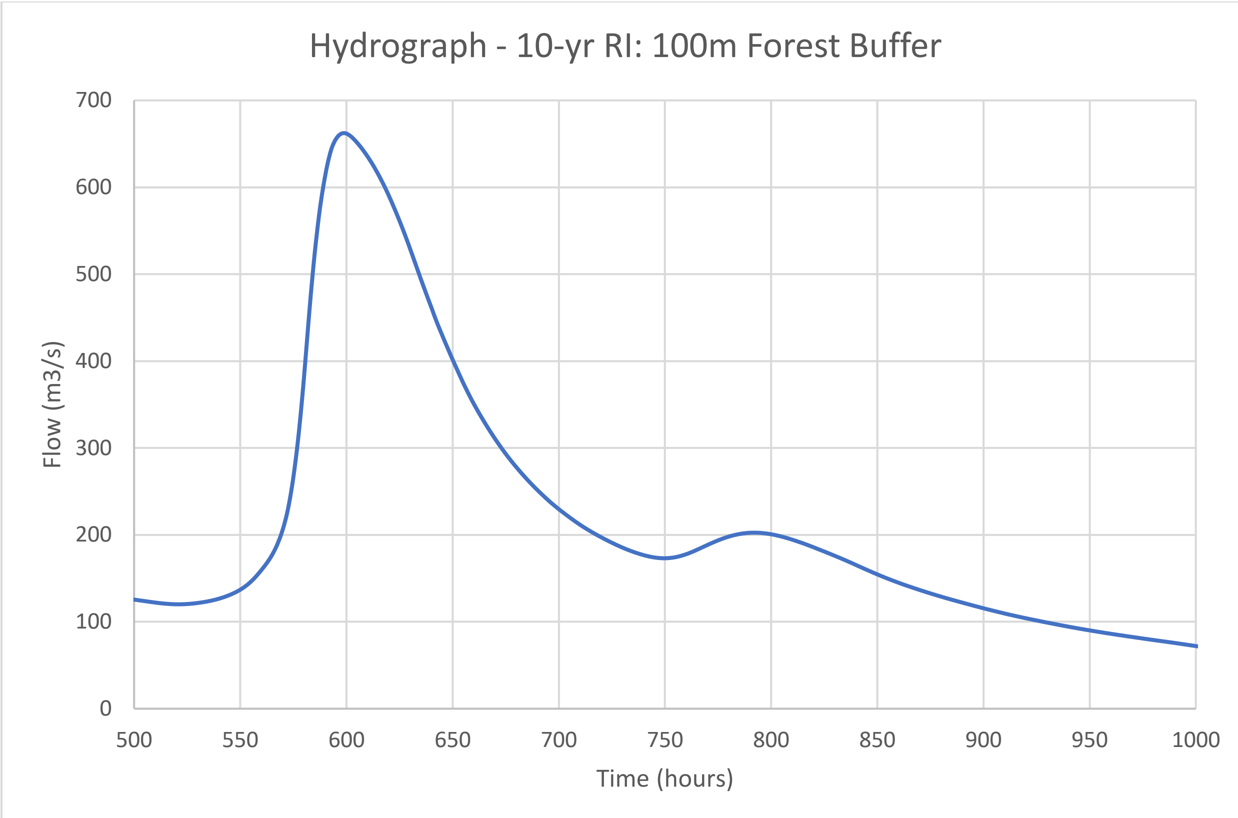
Hydrograph - 10-yr RI: 500m Forest Buffer
Flow (m3/s)
700
600
500
400
300
200
100
0
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

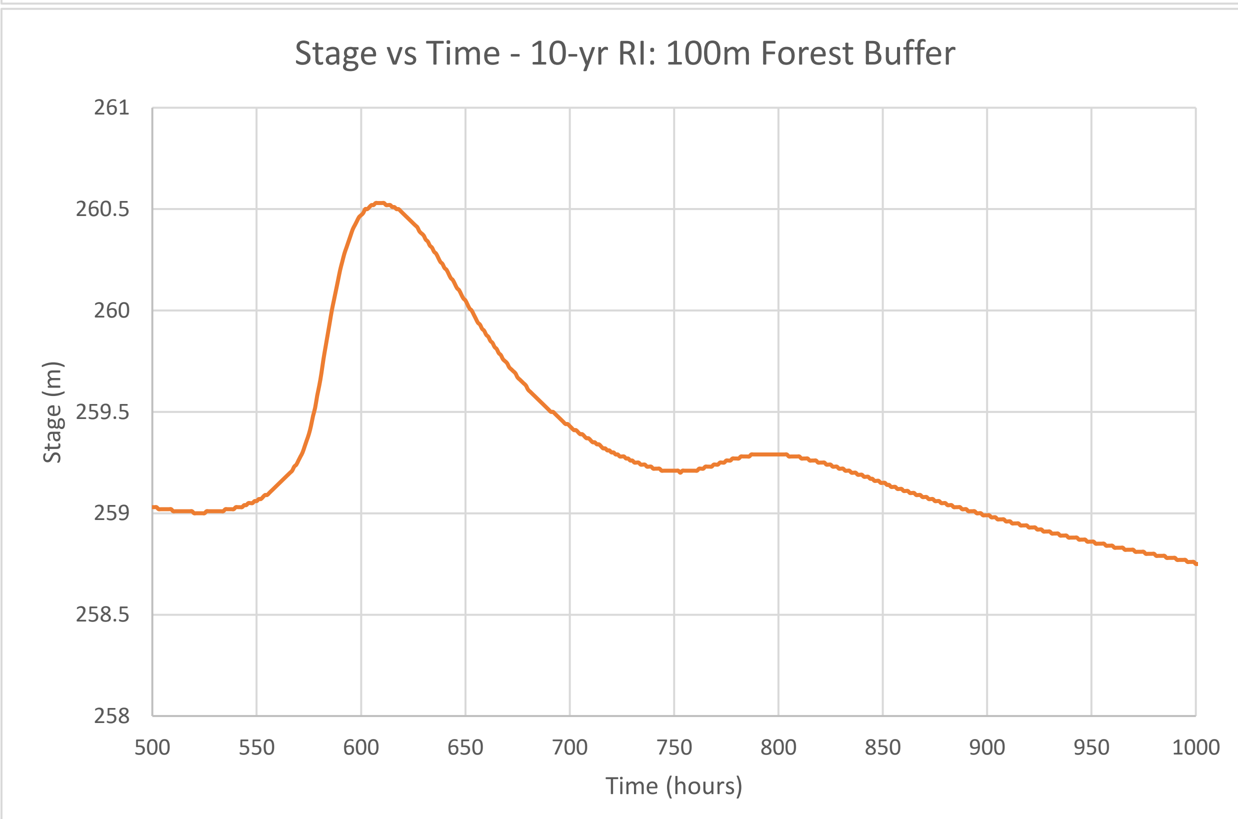


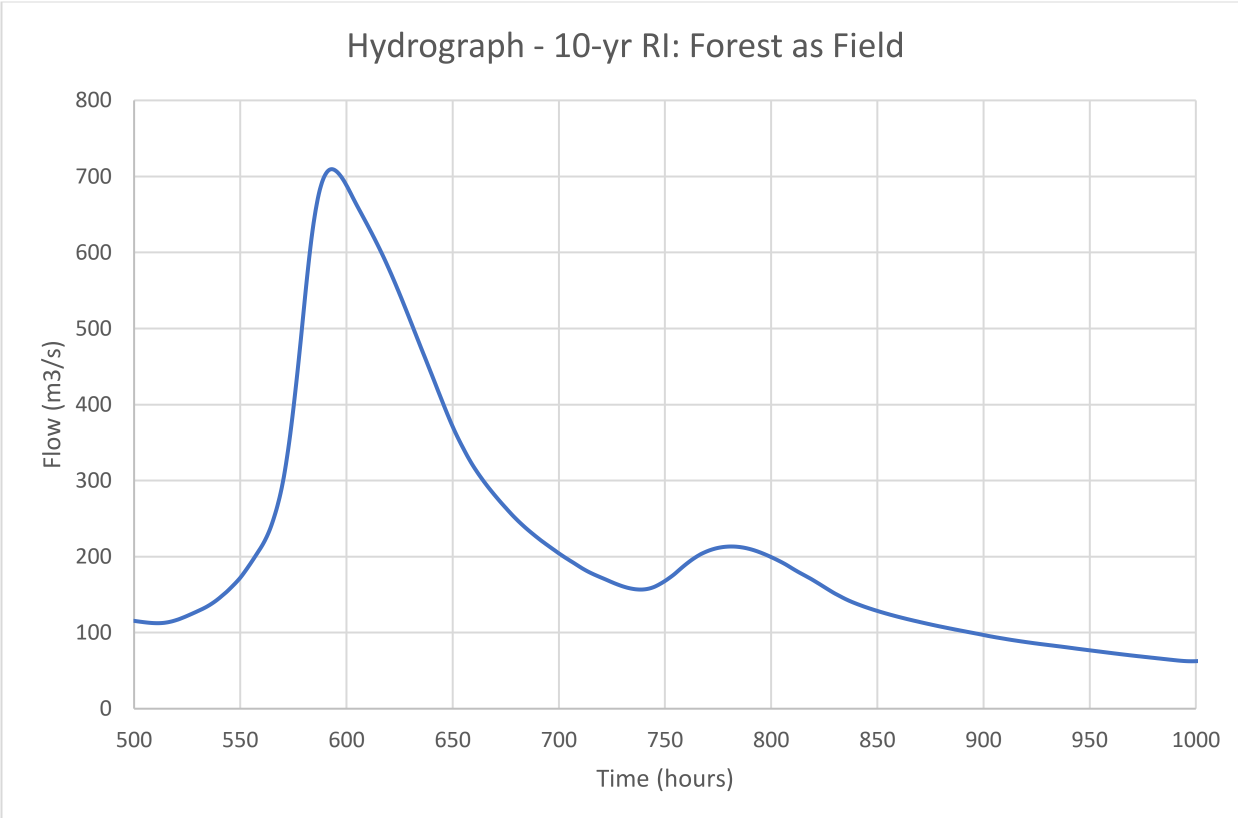
Stage vs Time - 10-yr RI: 500m Forest Buffer
Stage (m)
262
261.5
261
260.5
260
259.5
259
258.5
258
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

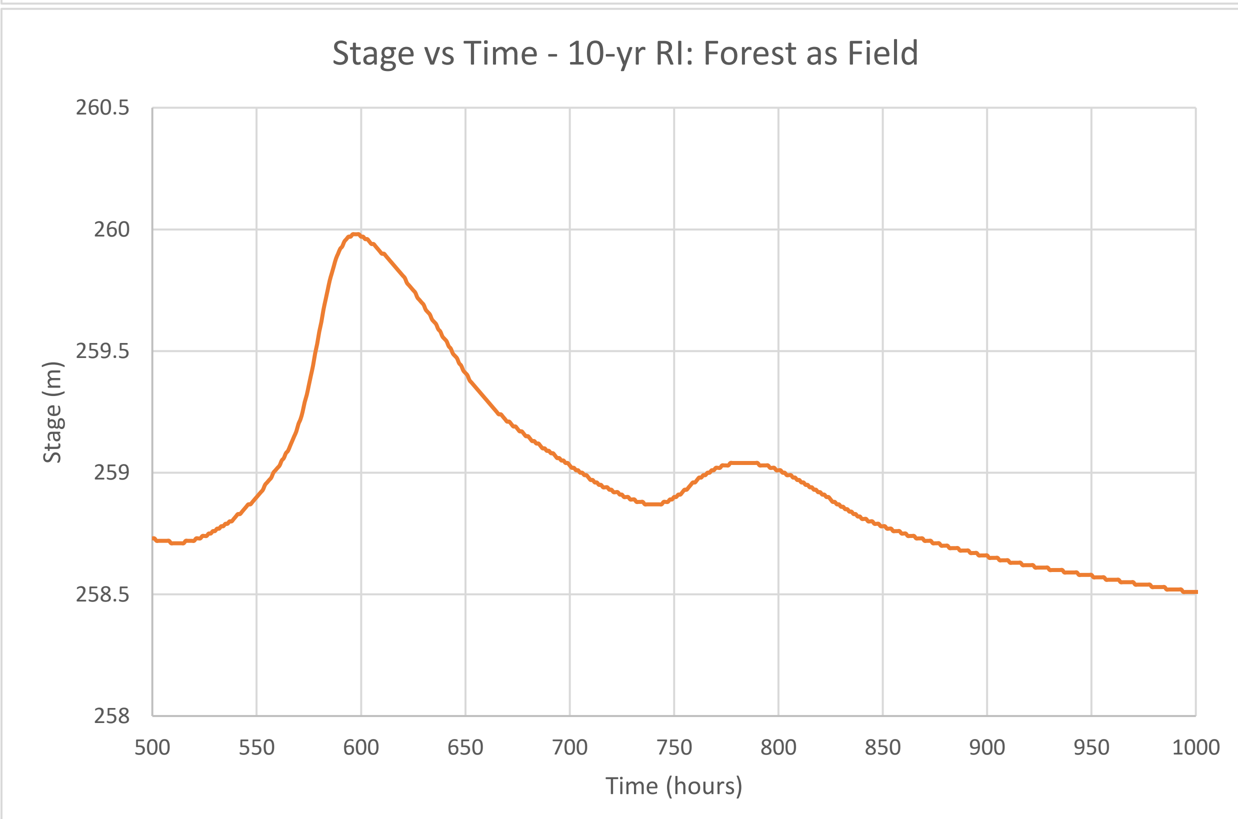

Hydrograph - 10-yr RI: 250m Forest Buffer
Flow (m3/s)
700
600
500
400
300
200
100
0
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

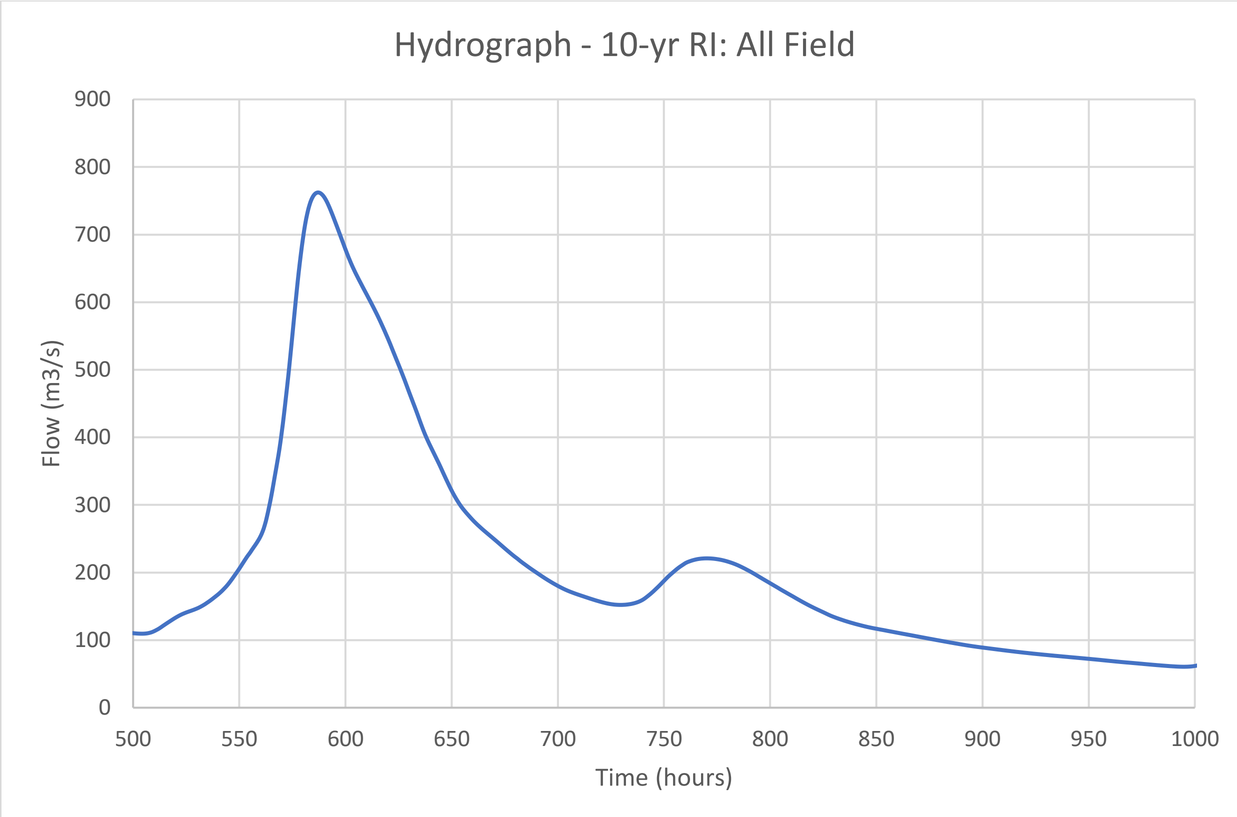

Stage vs Time - 10-yr RI: 250m Forest Buffer
Stage (m)
261.5
261
260.5
260
259.5
259
258.5
258
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)


Hydrograph - 10-yr RI: 100m Forest Buffer
Flow (m3/s)
0
100
200
300
400
500
600
700
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

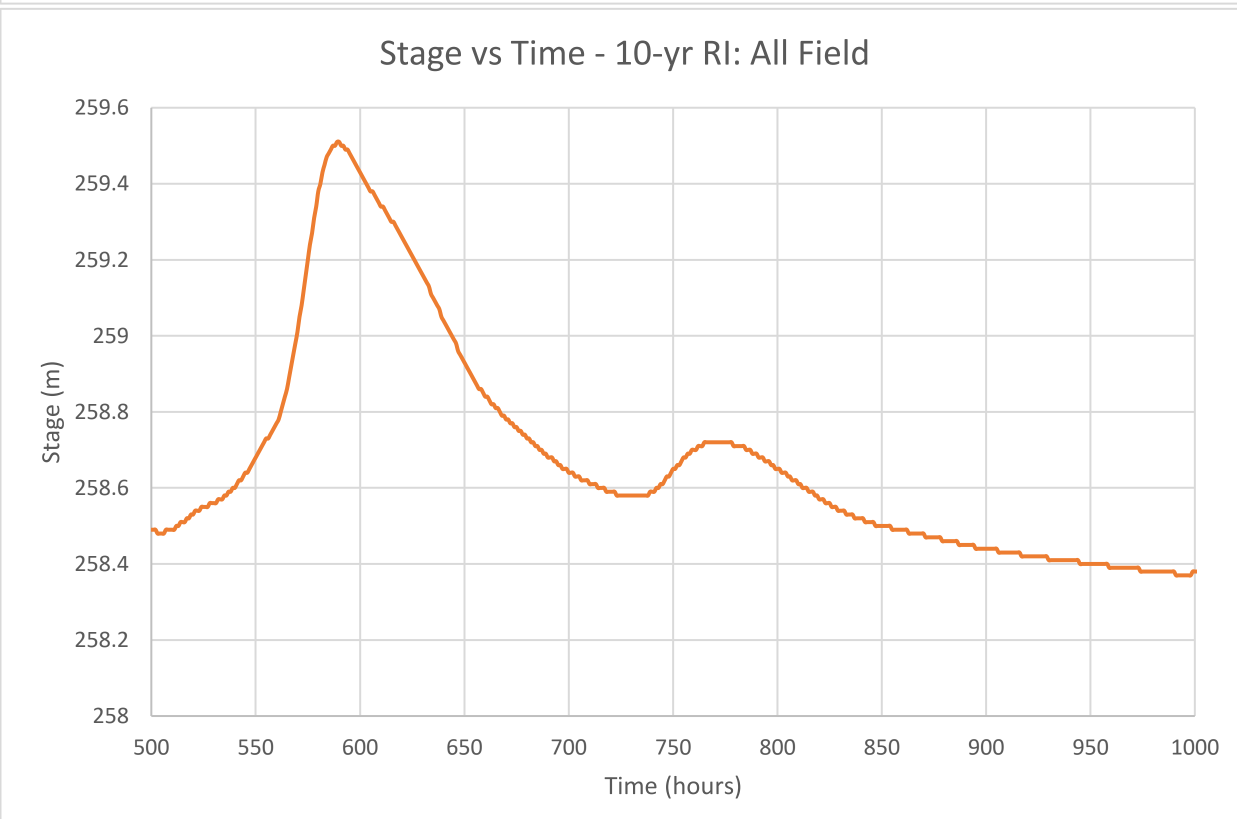

Stage vs Time - 10-yr RI: 100m Forest Buffer
Stage (m)
258
258.5
259
259.5
260
260.5
261
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)


Hydrograph - 10-yr RI: Forest as Field
Flow (m3/s)
0
100
200
300
400
500
600
700
800
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

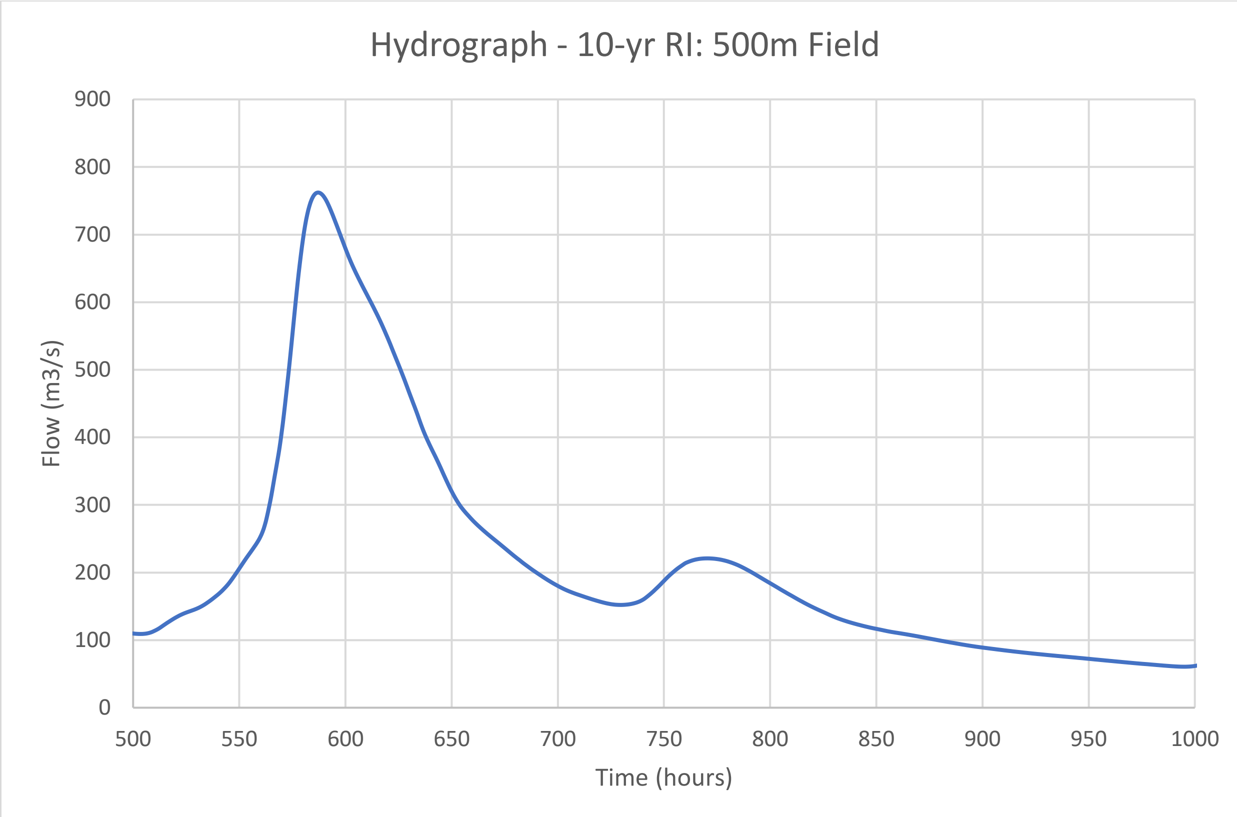

Stage vs Time - 10-yr RI: Forest as Field
Stage (m)
258
258.5
259
259.5
260
260.5
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

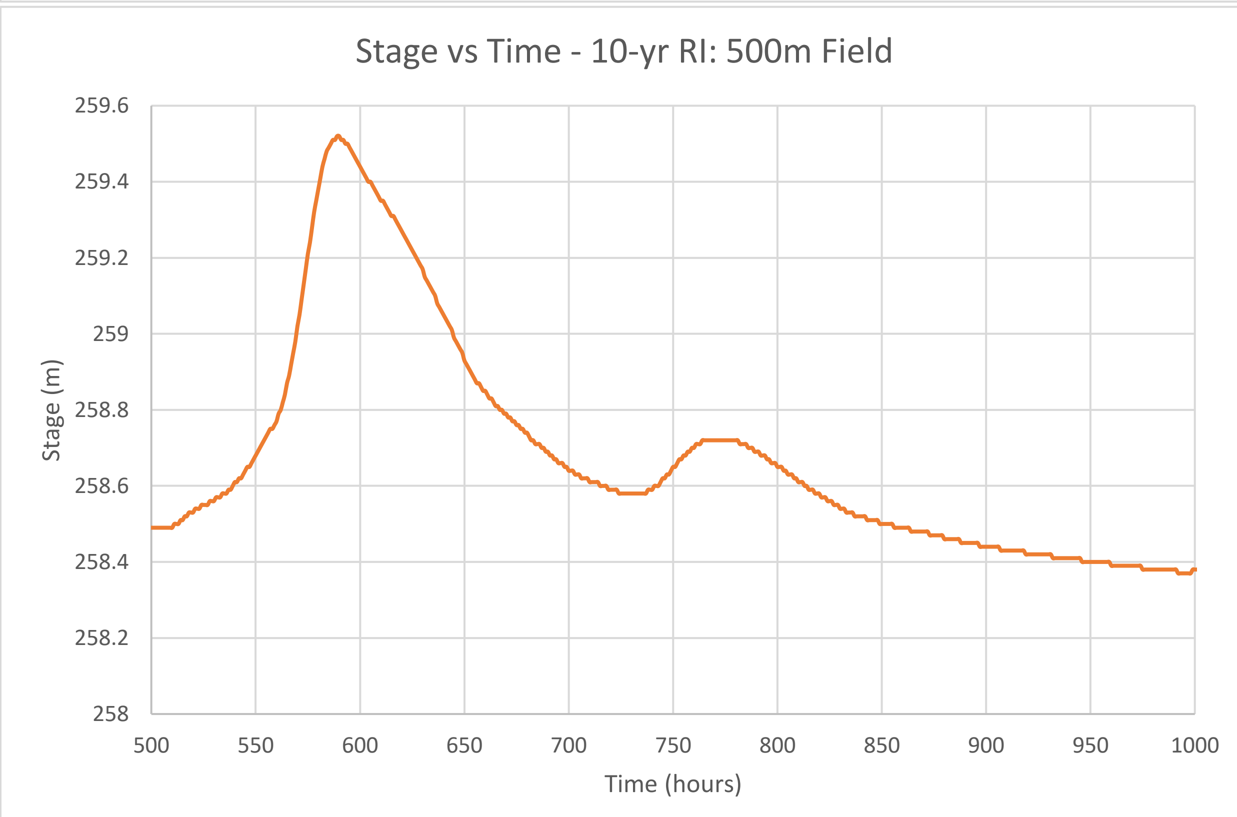


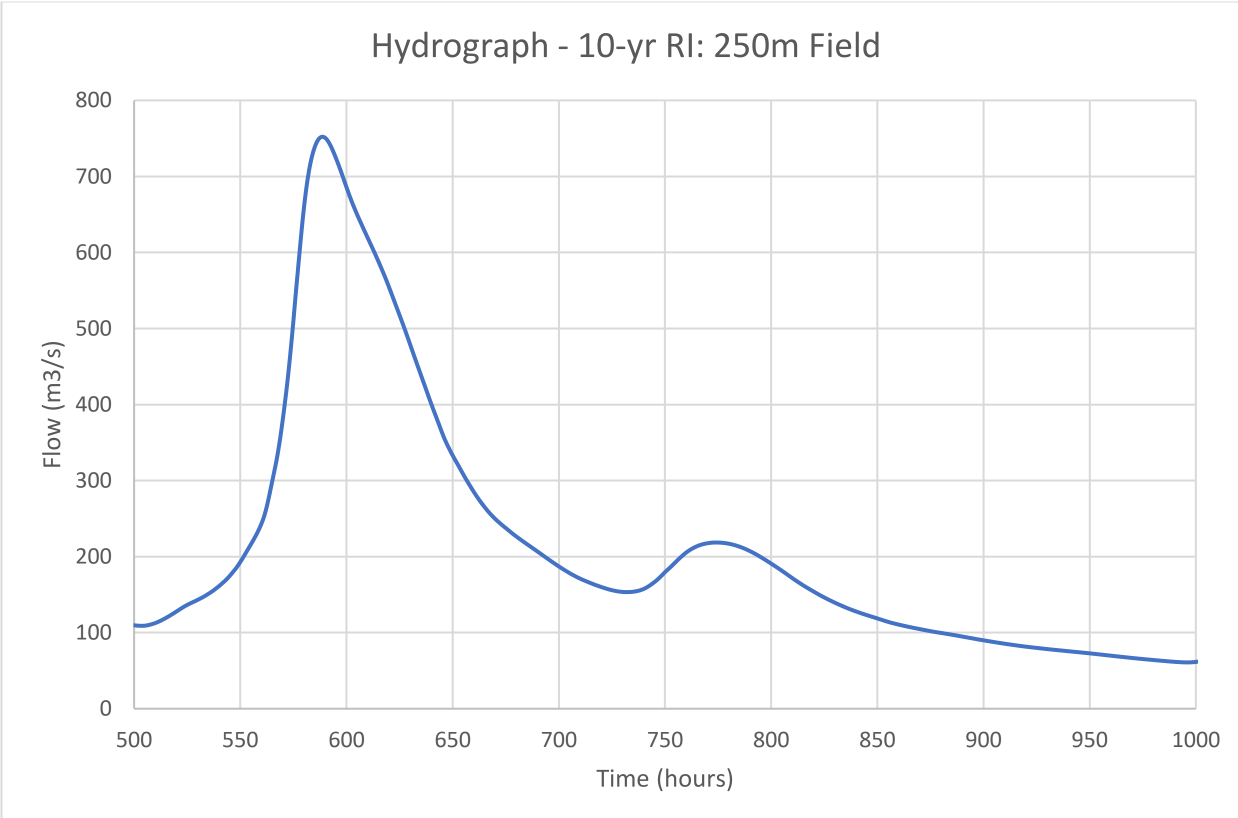
Hydrograph - 10-yr RI: All Field
Flow (m3/s)
900
800
700
600
500
400
300
200
100
0
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

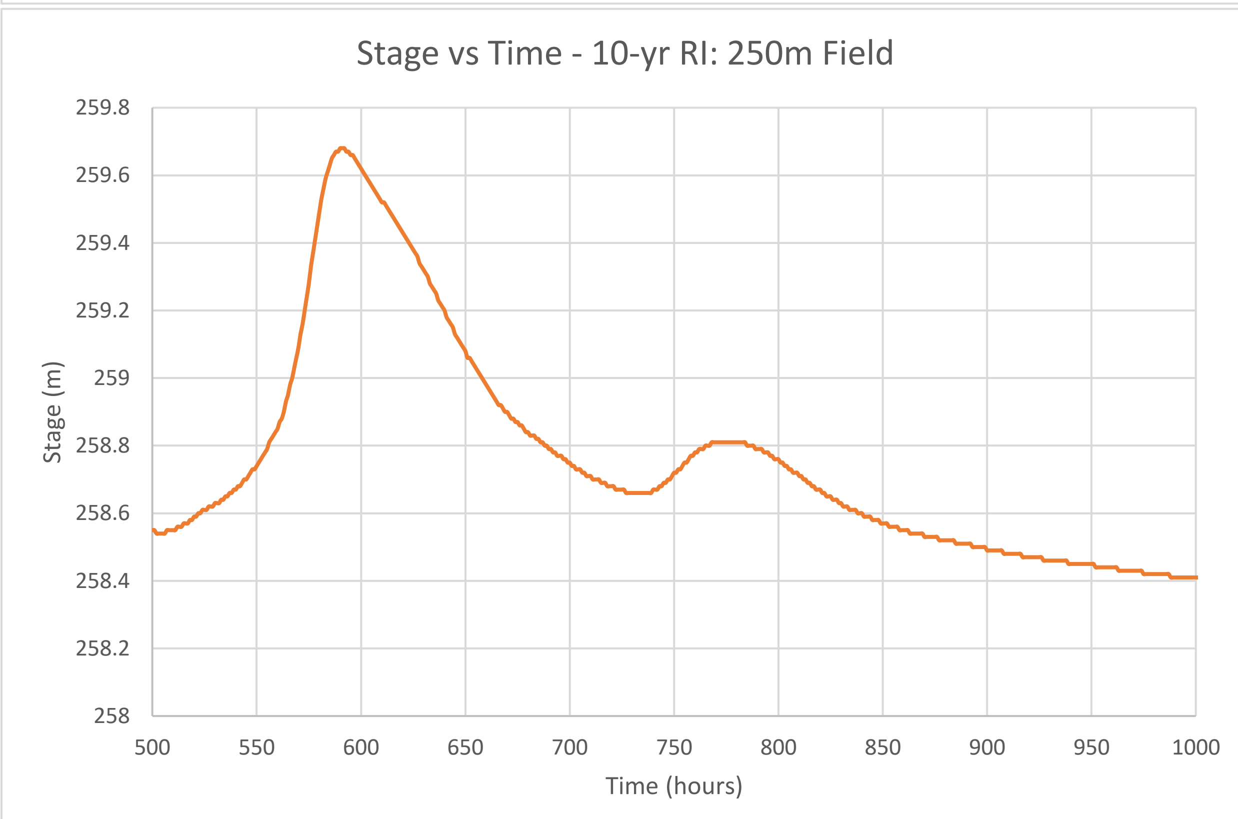


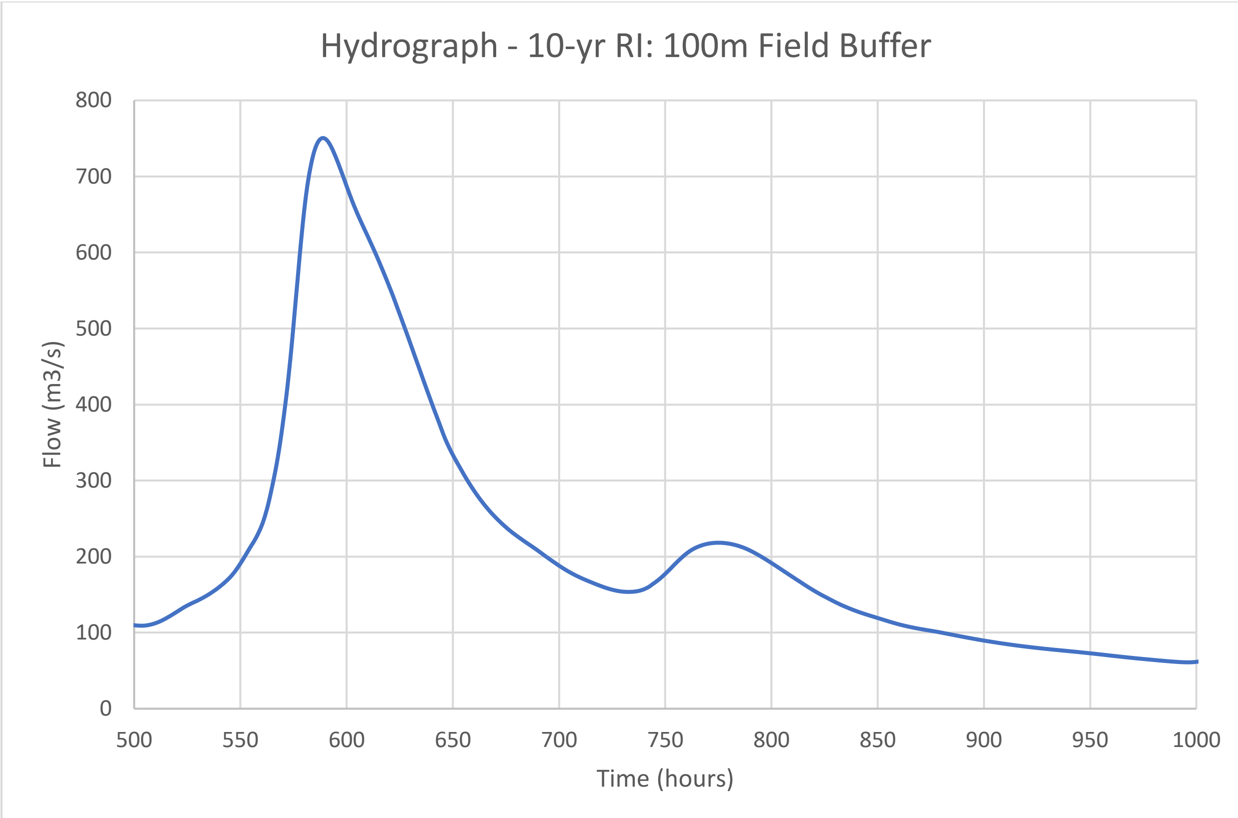
Stage vs Time - 10-yr RI: All Field
Stage (m)
259.6
259.4
259.2
259
258.8
258.6
258.4
258.2
258
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

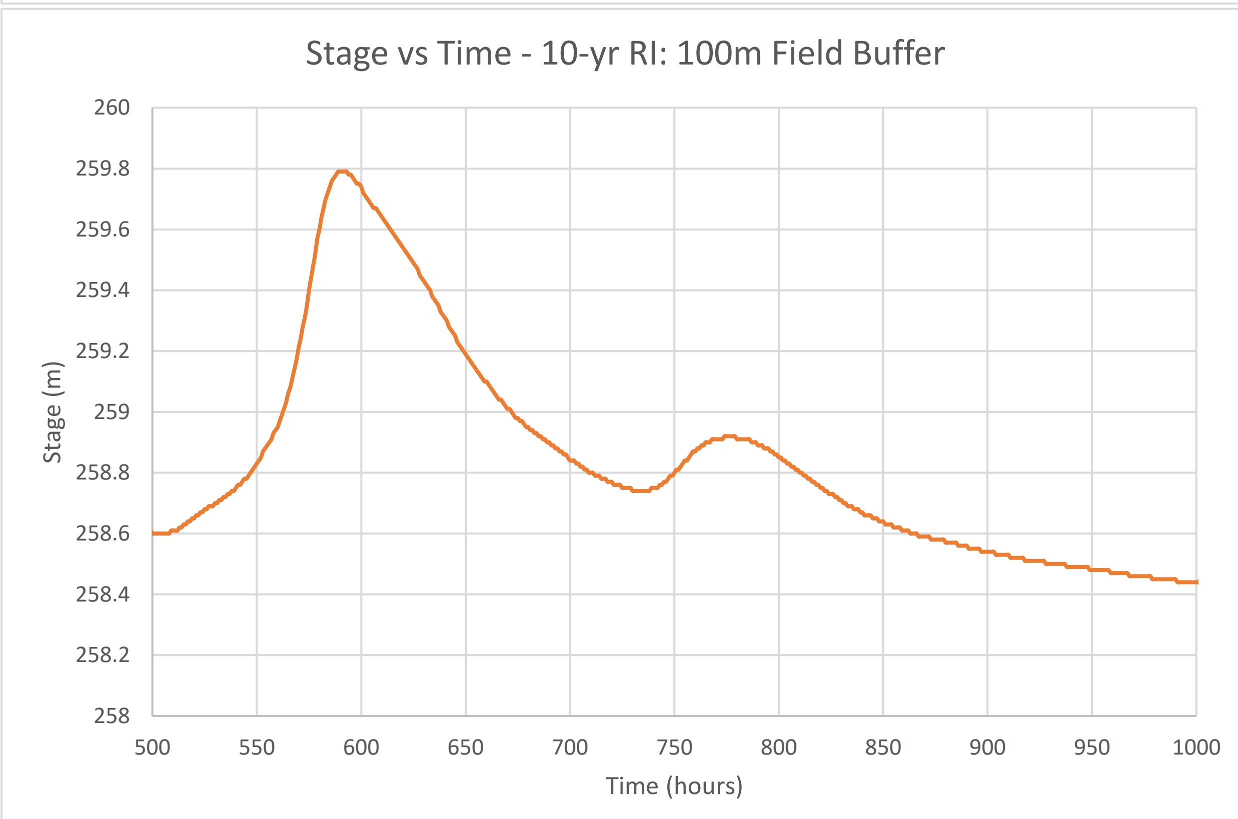

Hydrograph - 10-yr RI: 500m Field
Flow (m3/s)
0
100
200
300
400
500
600
700
800
900
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

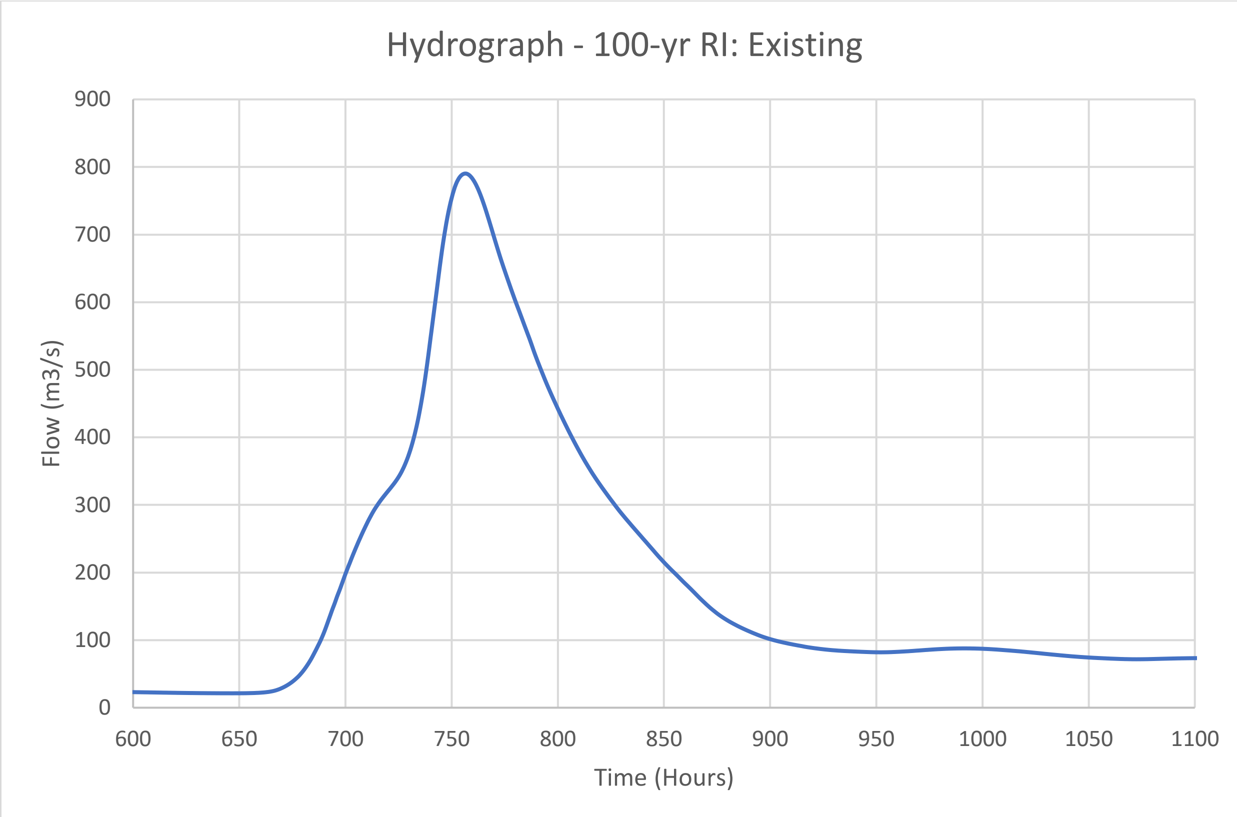

Stage vs Time - 10-yr RI: 500m Field
Stage (m)
258
258.2
258.4
258.6
258.8
259
259.2
259.4
259.6
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)


Hydrograph - 10-yr RI: 250m Field
Flow (m3/s)
0
100
200
300
400
500
600
700
800
Time (hours)
500
550
600
650
700
750
800
850
900
950
1000

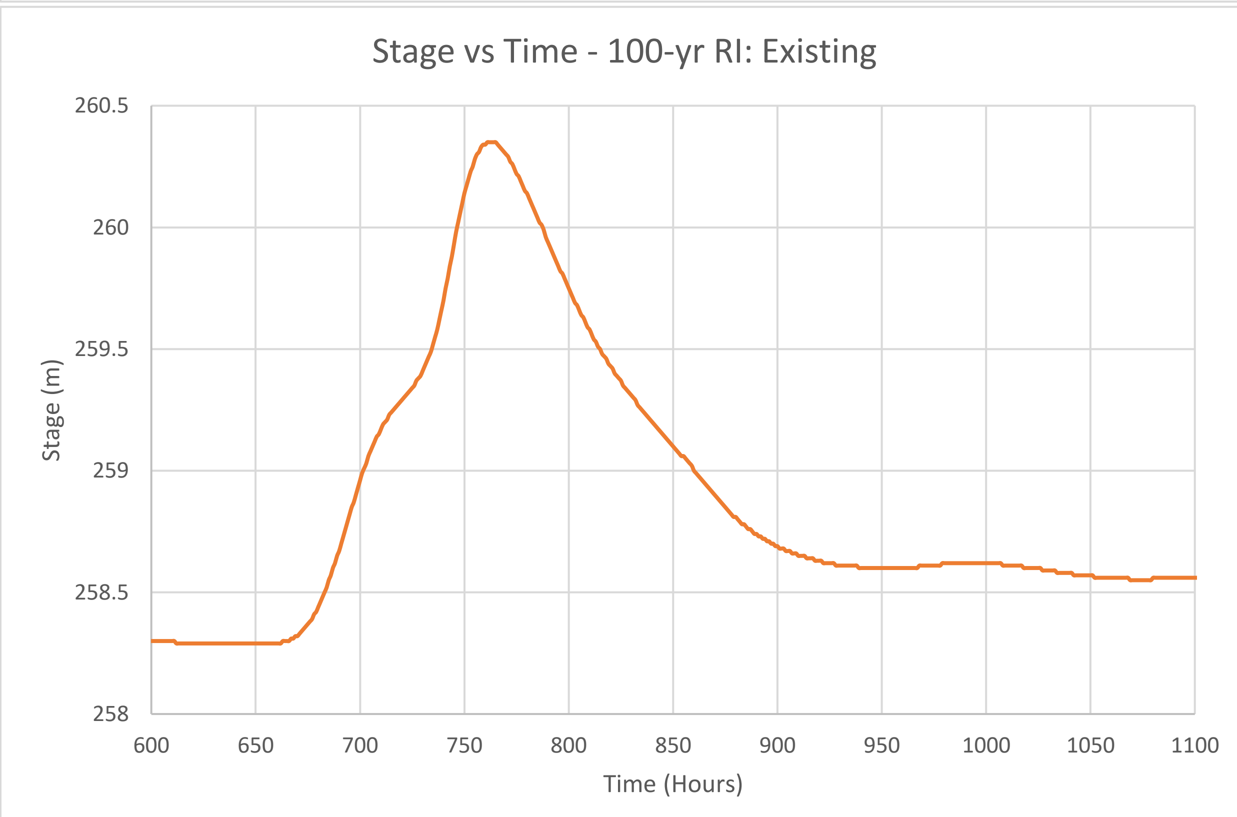

Stage vs Time - 10-yr RI: 250m Field
Stage (m)
258
258.2
258.4
258.6
258.8
259
259.2
259.4
259.6
259.8
Time (hours)
500
550
600
650
700
750
800
850
900
950
1000


Hydrograph - 10-yr RI: 100m Field Buffer
Flow (m3/s)
800
700
600
500
400
300
200
100
0
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)

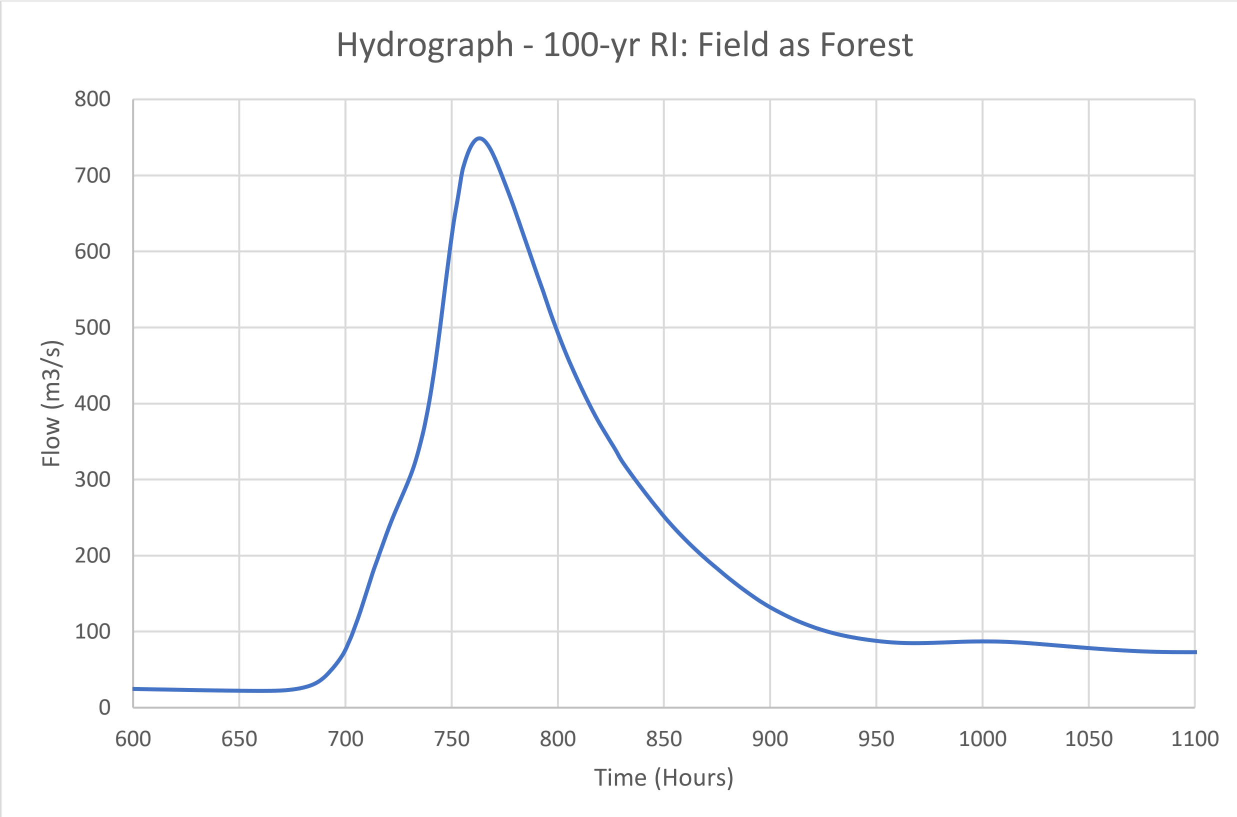

Stage vs Time - 10-yr RI: 100m Field Buffer
Stage (m)
260
259.8
259.6
259.4
259.2
259
258.8
258.6
258.4
258.2
258
500
550
600
650
700
750
800
850
900
950
1000
Time (hours)



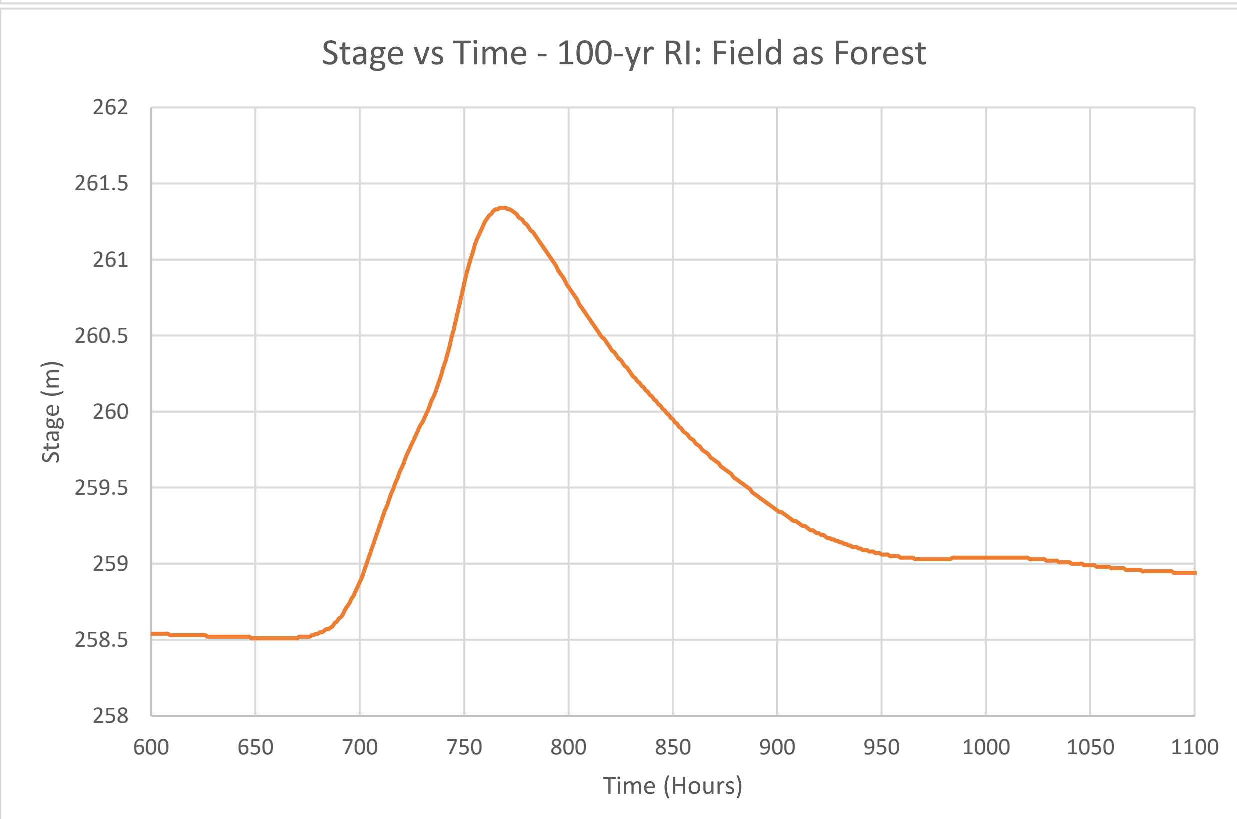
Hydrograph - 100-yr RI: Existing
Flow (m3/s)
900
800
700
600
500
400
300
200
100
0
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)



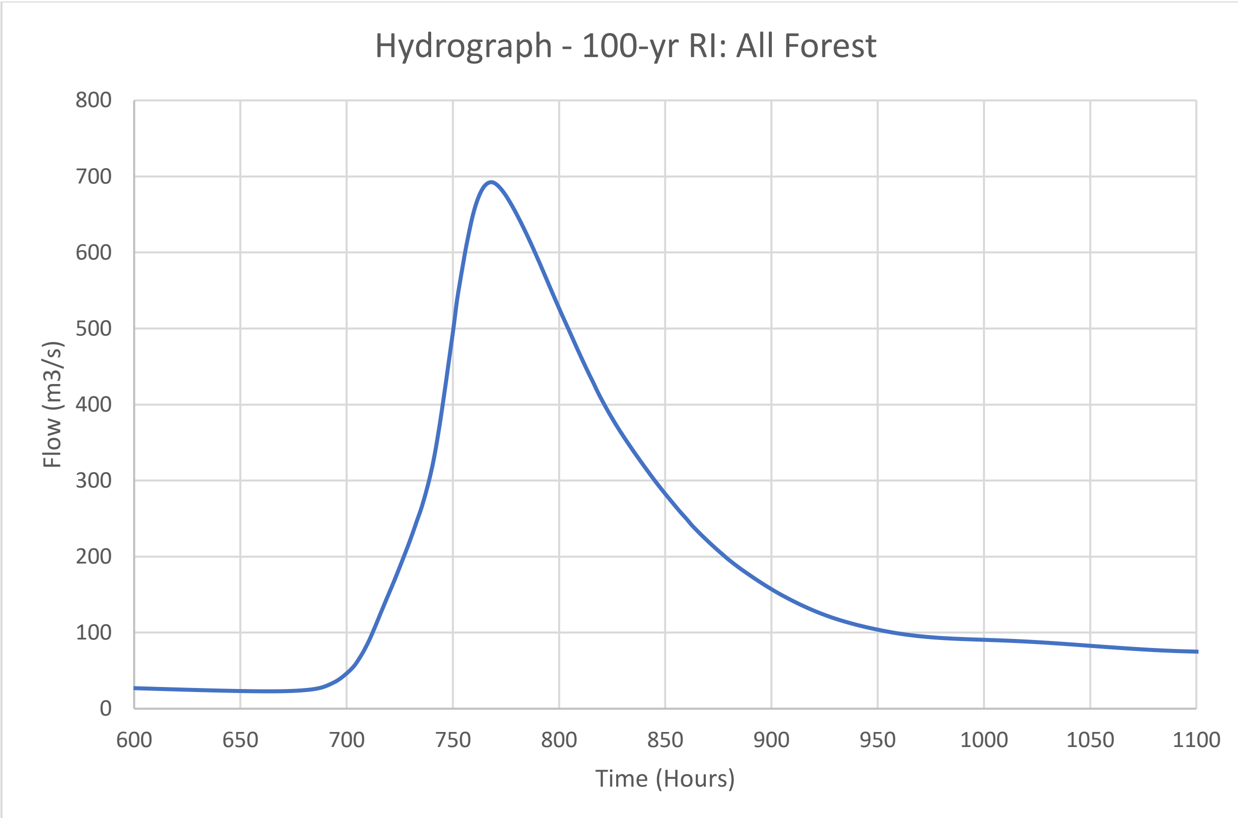
Stage vs Time - 100-yr RI: Existing
Stage (m)
260.5
260
259.5
259
258.5
258
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

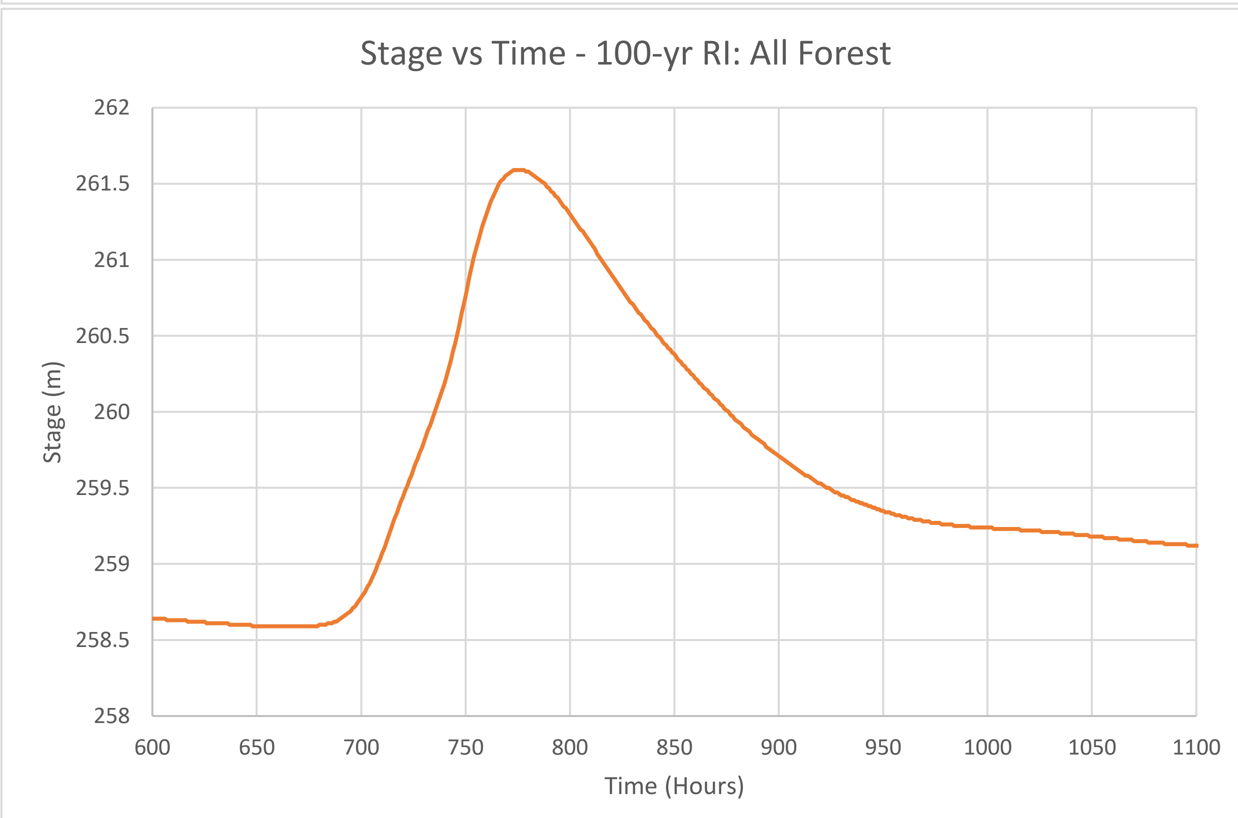


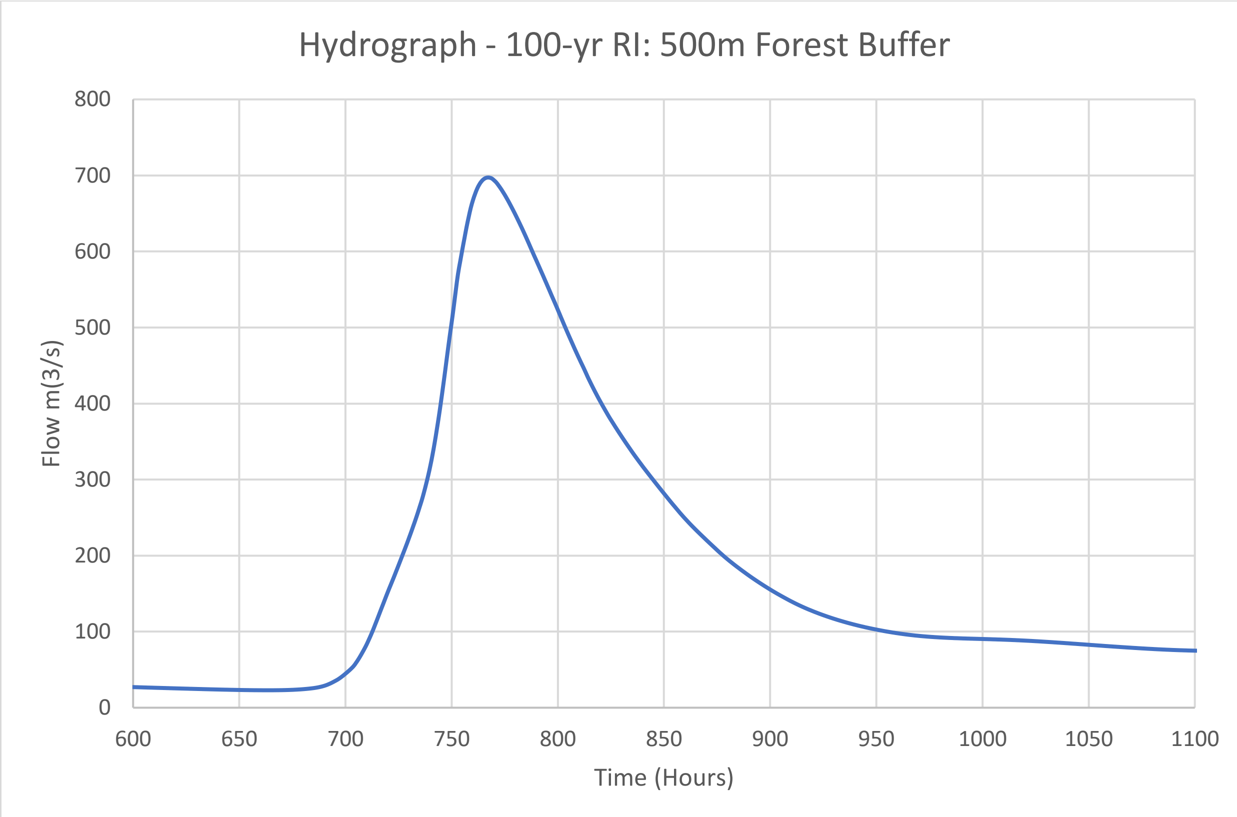
Hydrograph - 100-yr RI: Field as Forest
Flow (m3/s)
0
100
200
300
400
500
600
700
800
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

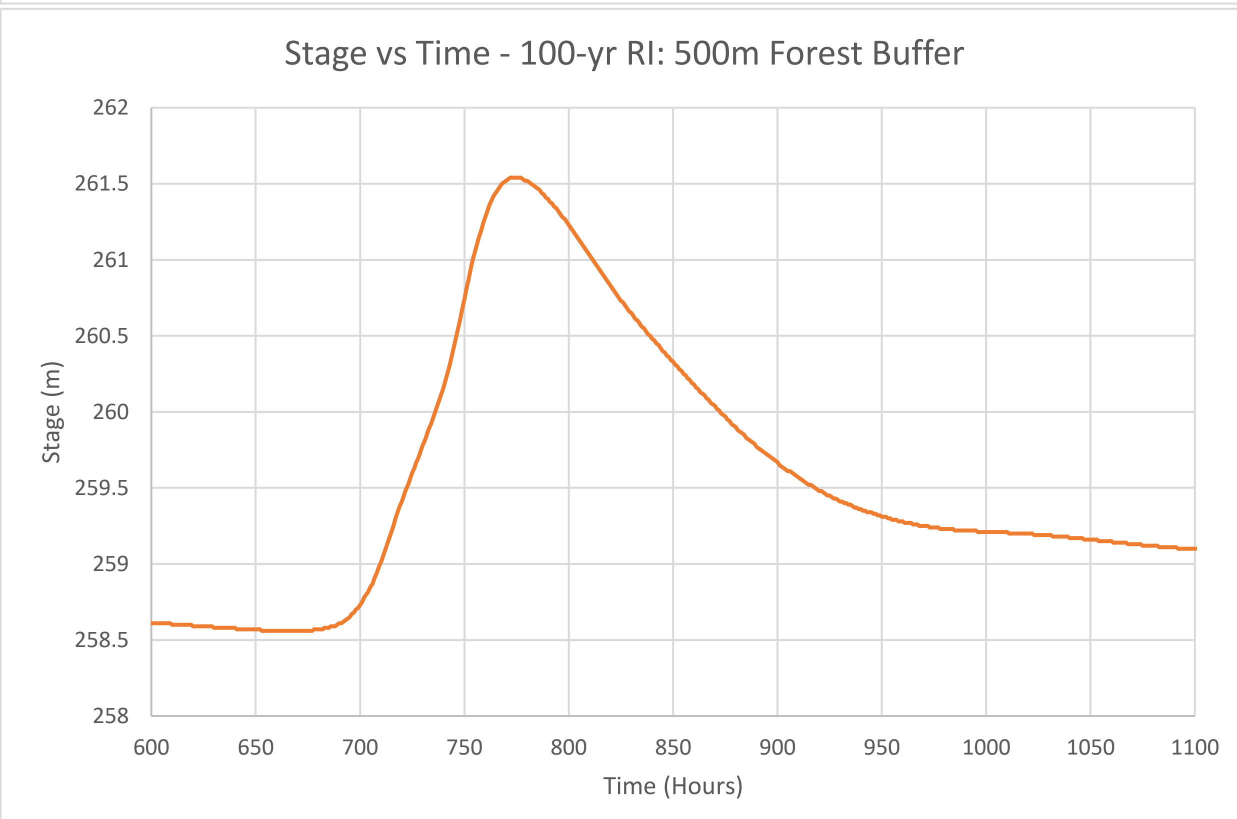


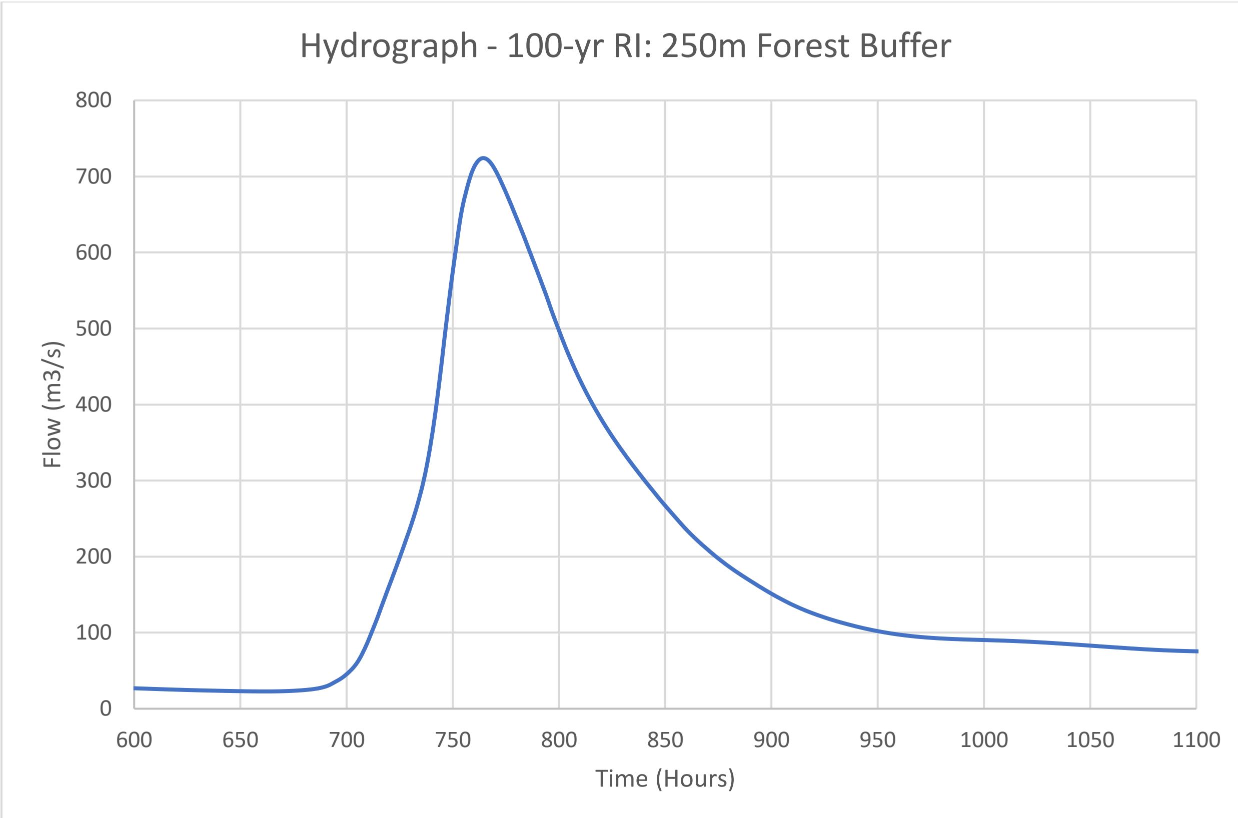
Stage vs Time - 100-yr RI: Field as Forest
Stage (m)
258
258.5
259
259.5
260
260.5
261
261.5
262
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

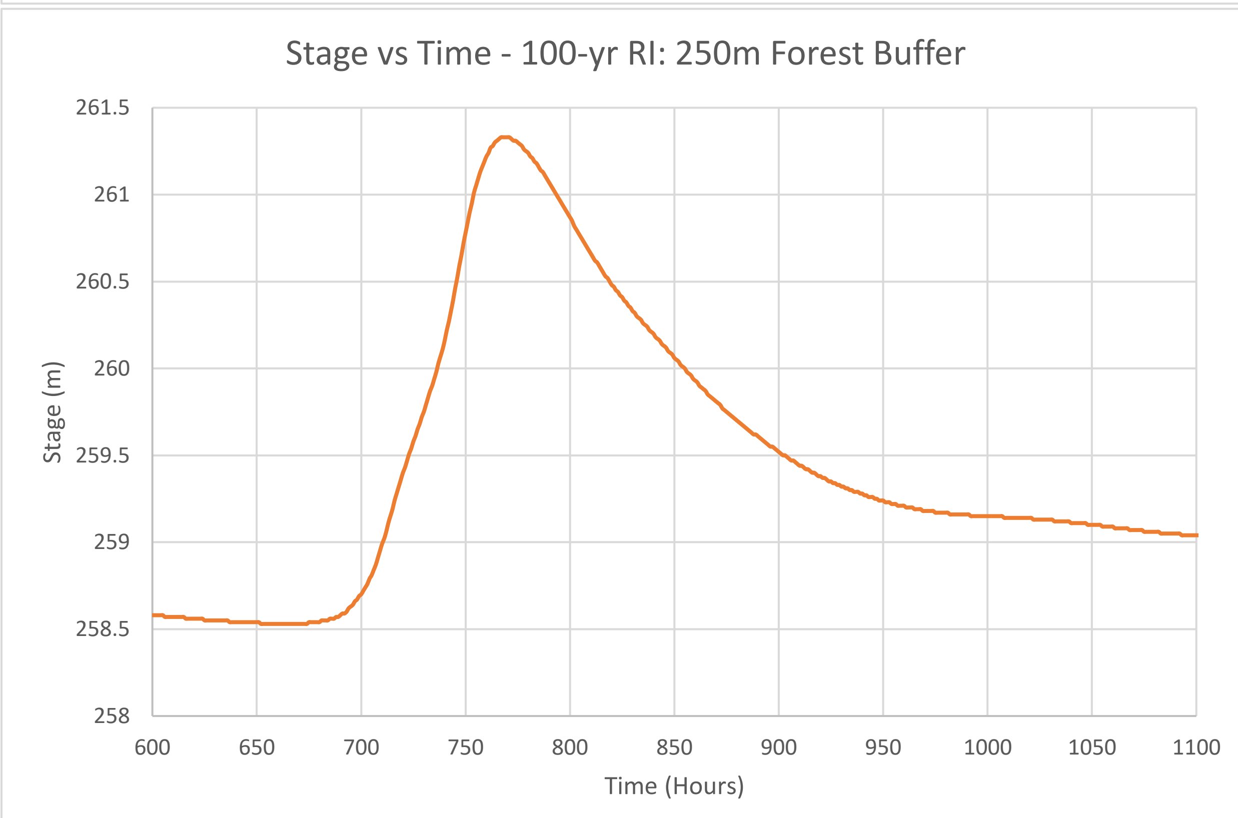

Hydrograph - 100-yr RI: All Forest
Flow (m3/s)
0
100
200
300
400
500
600
700
800
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

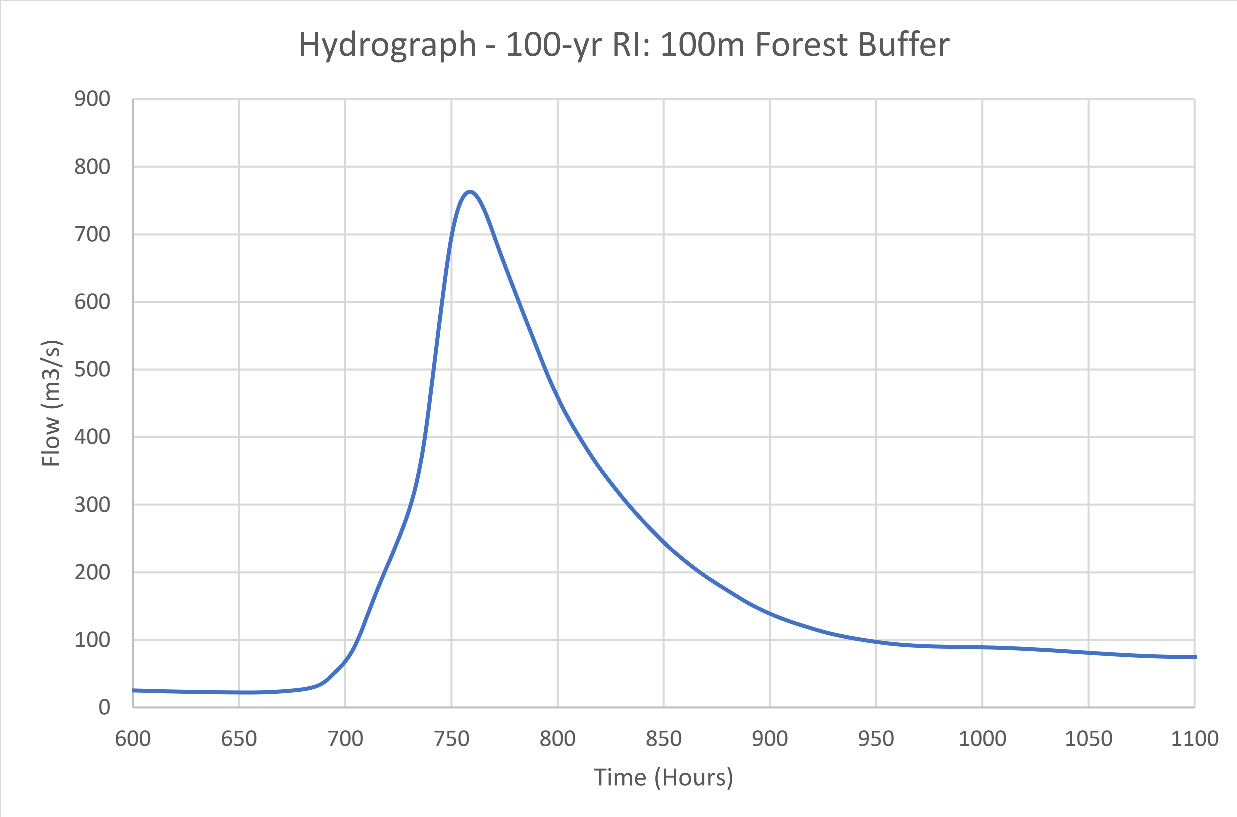

Stage vs Time - 100-yr RI: All Forest
Stage (m)
258
258.5
259
259.5
260
260.5
261
261.5
262
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

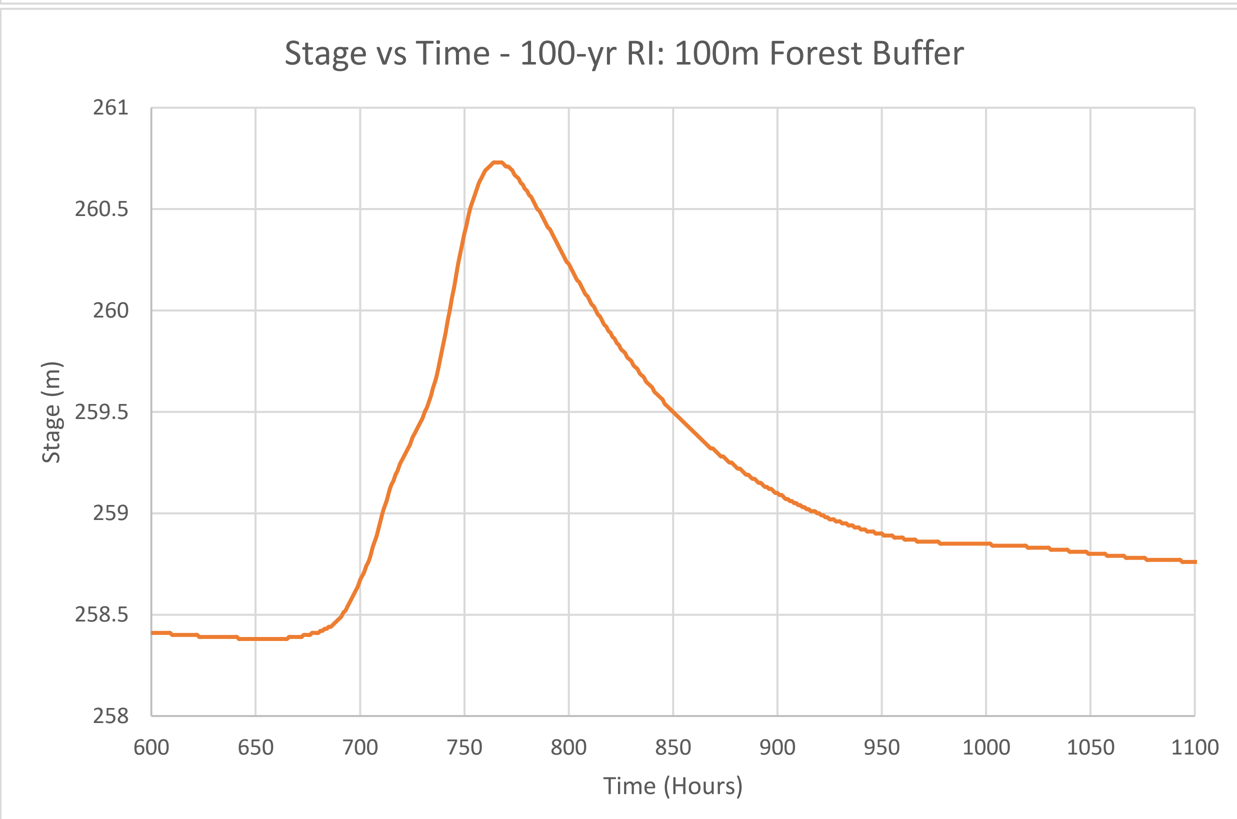

Hydrograph - 100-yr RI: 500m Forest Buffer
Flow m(3/s)
0
100
200
300
400
500
600
700
800
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

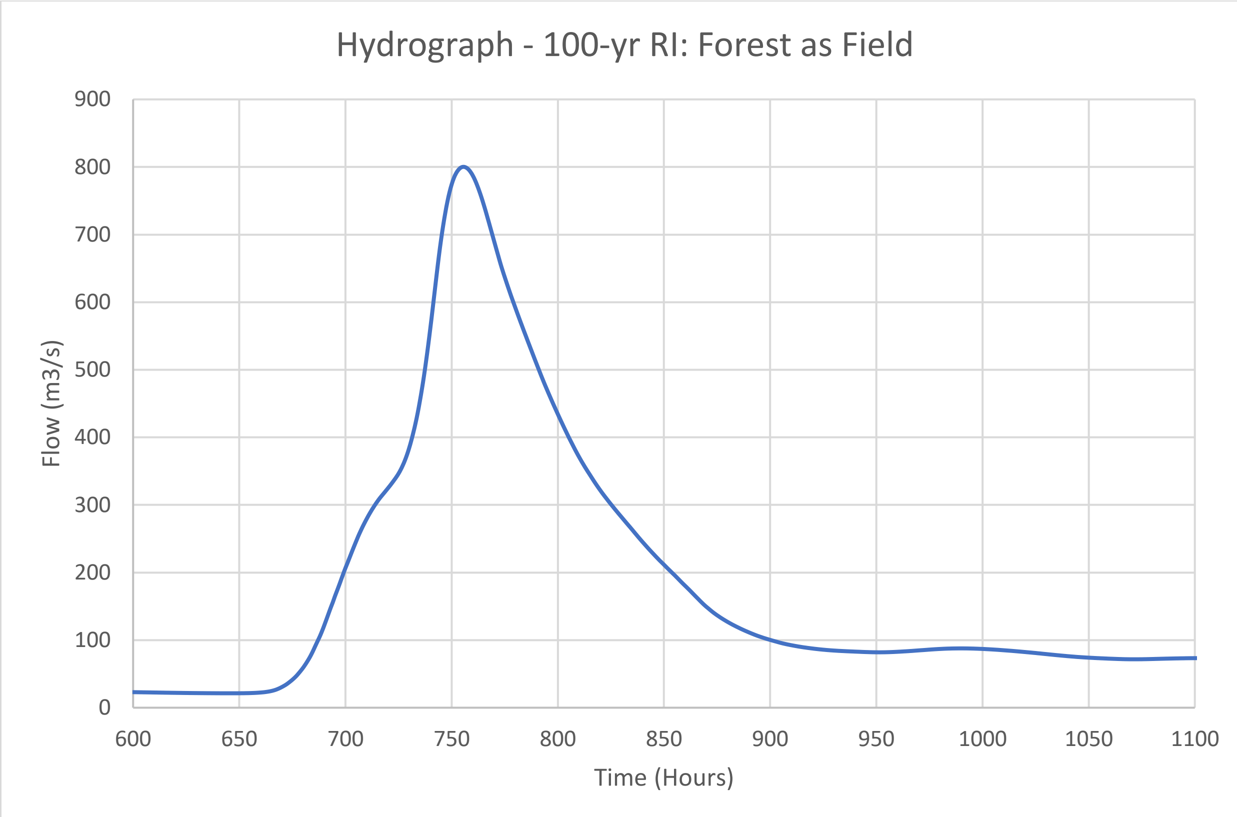

Stage vs Time - 100-yr RI: 500m Forest Buffer
Stage (m)
258
258.5
259
259.5
260
260.5
261
261.5
262
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Hydrograph - 100-yr RI: 250m Forest Buffer
800
700
600
500
400
300
200
100
0
Flow (m3/s)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

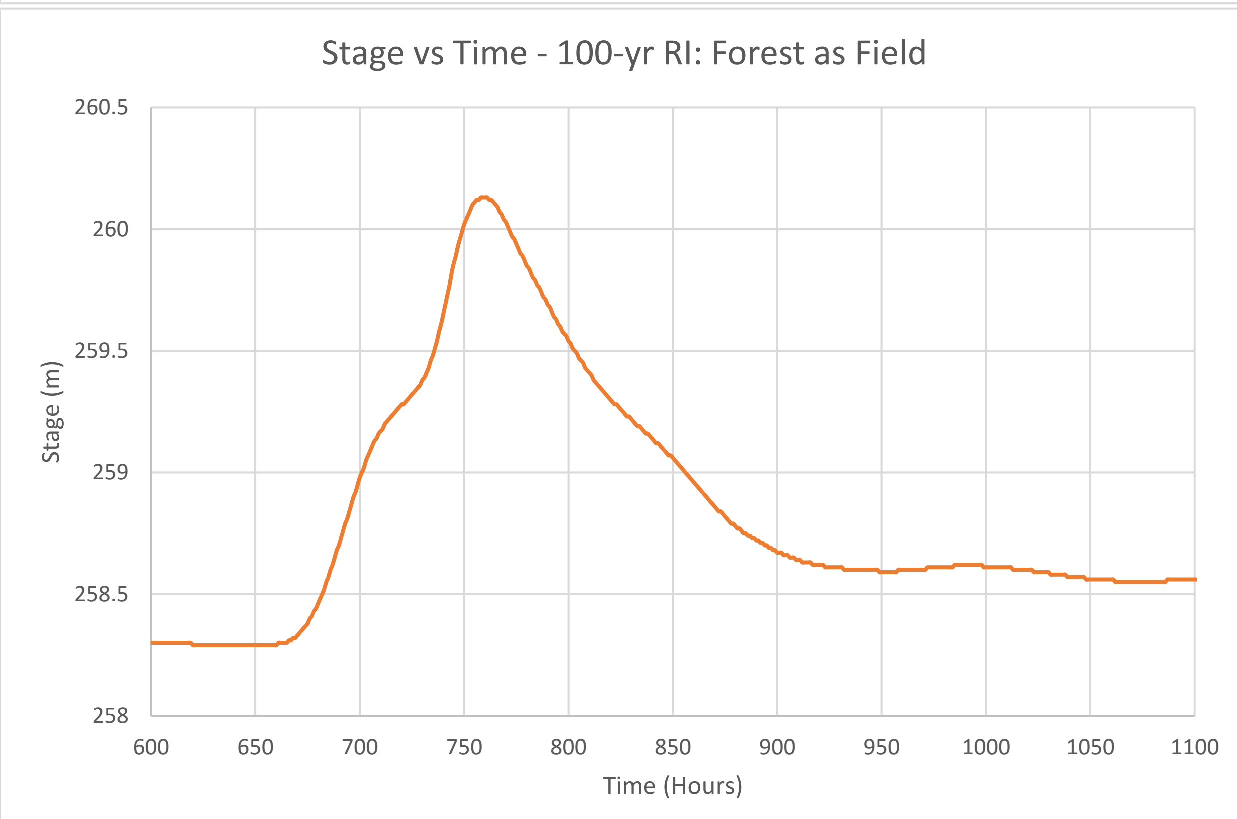

Stage vs Time - 100-yr RI: 250m Forest Buffer
261.5
261
260.5
260
259.5
259
258.5
258
Stage (m)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Hydrograph - 100-yr RI: 100m Forest Buffer
Flow (m3/s)
900
800
700
600
500
400
300
200
100
0
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

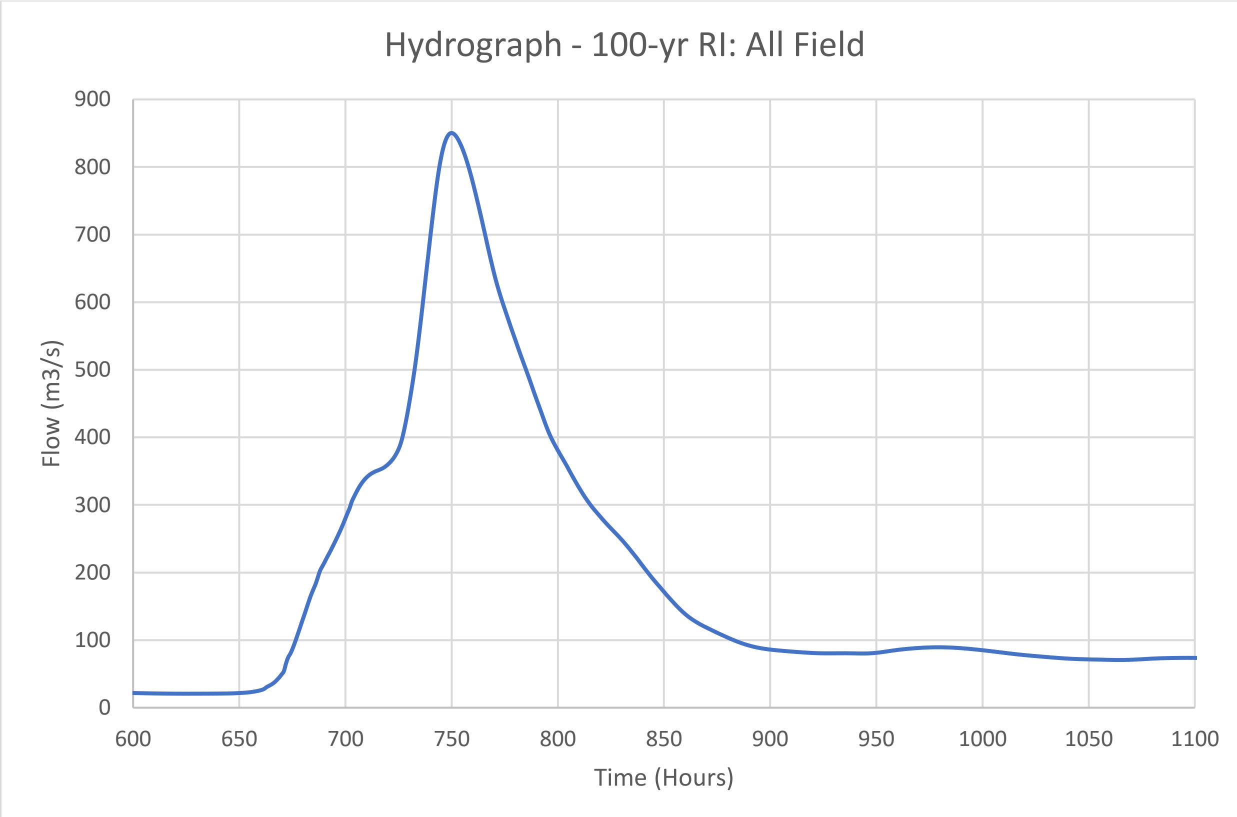

Stage vs Time - 100-yr RI: 100m Forest Buffer
Stage (m)
261
260.5
260
259.5
259
258.5
258
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)



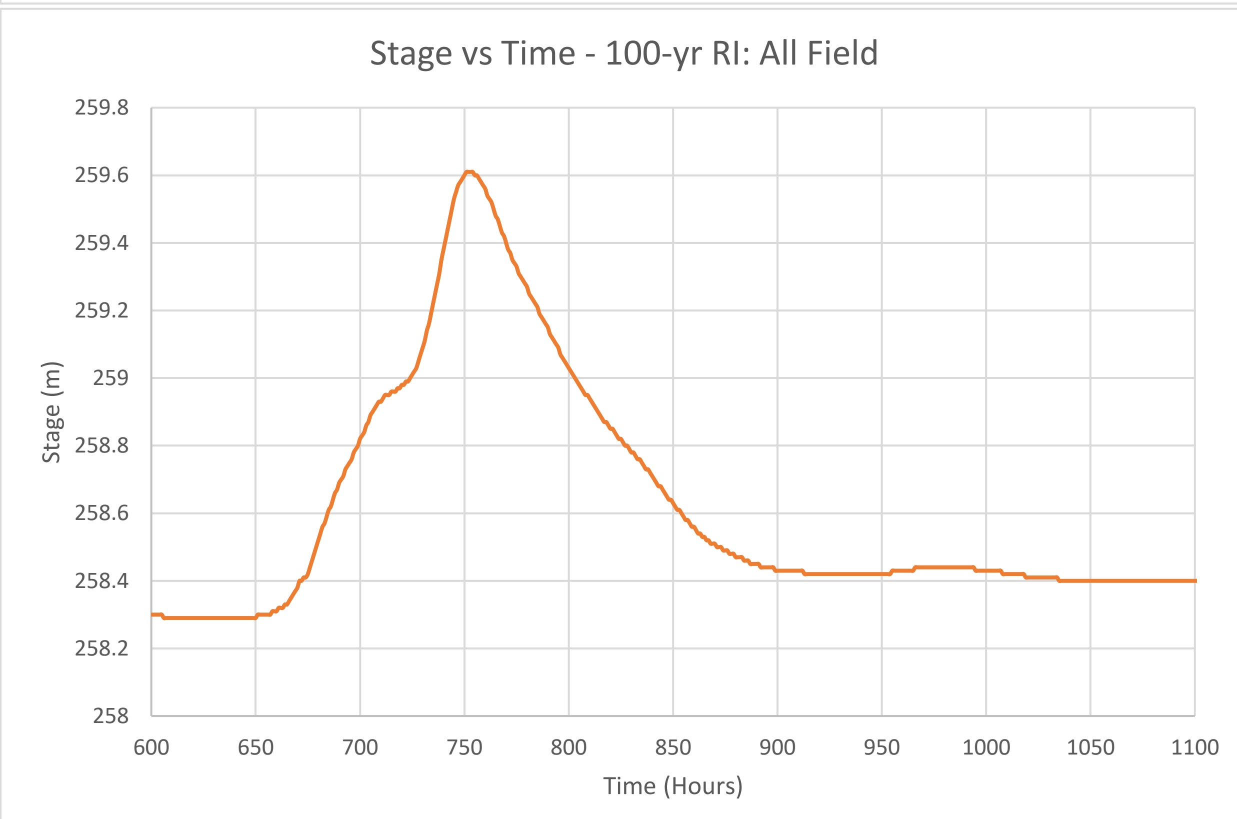
Hydrograph - 100-yr RI: Forest as Field
Flow (m3/s)
900
800
700
600
500
400
300
200
100
0
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)



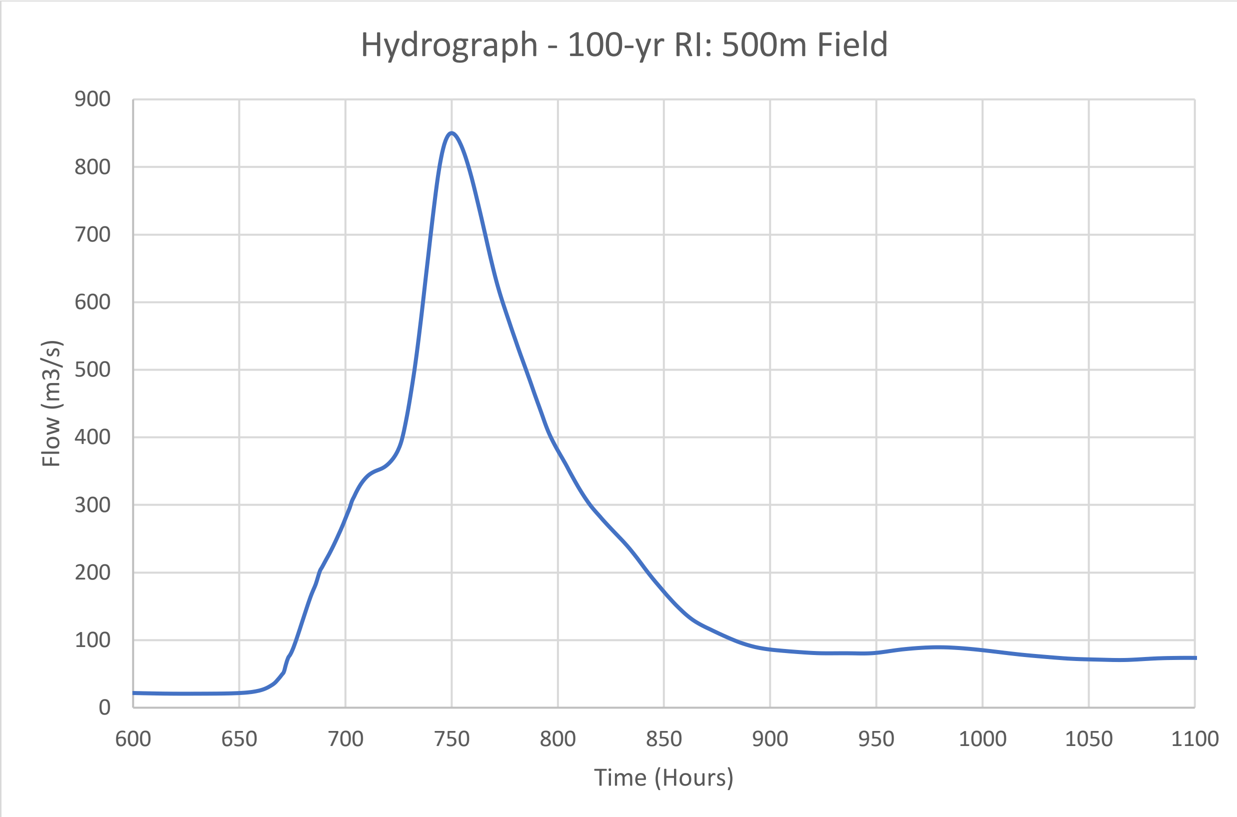
Stage vs Time - 100-yr RI: Forest as Field
Stage (m)
260.5
260
259.5
259
258.5
258
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

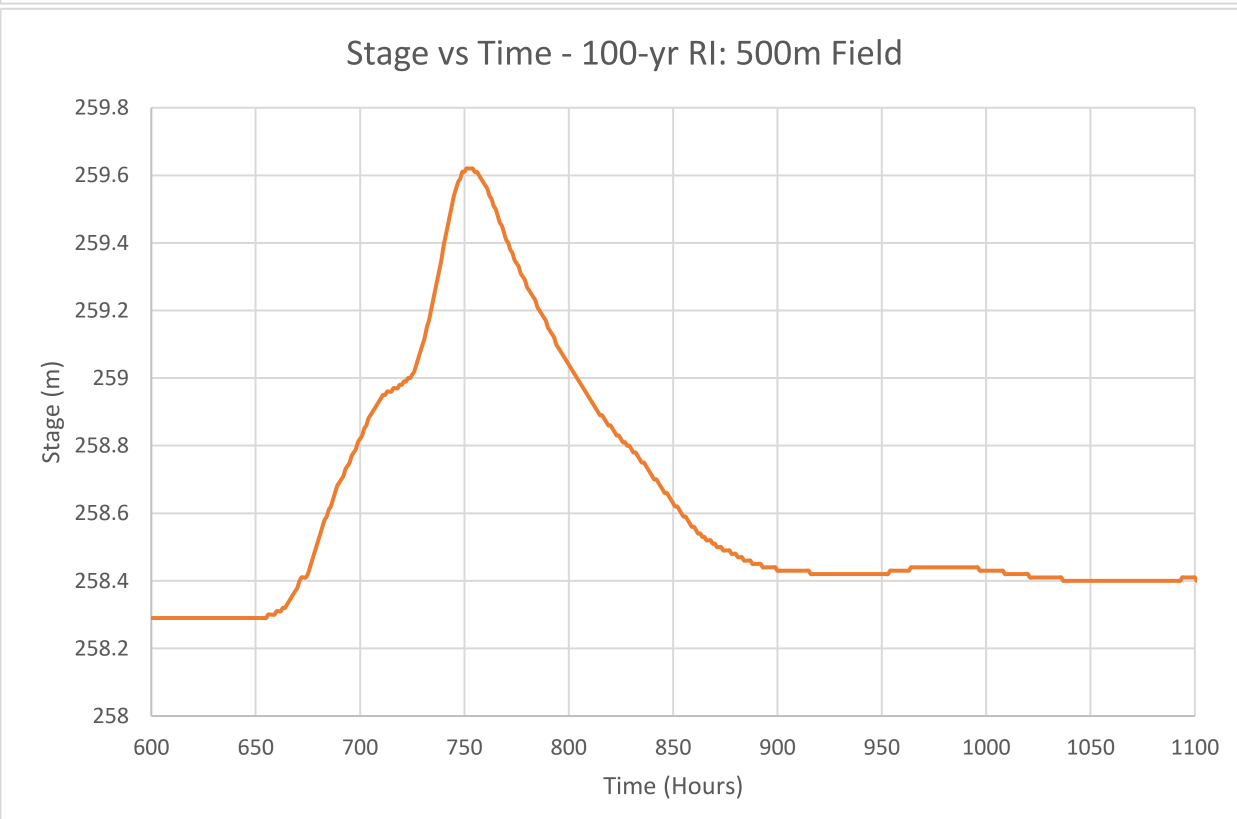


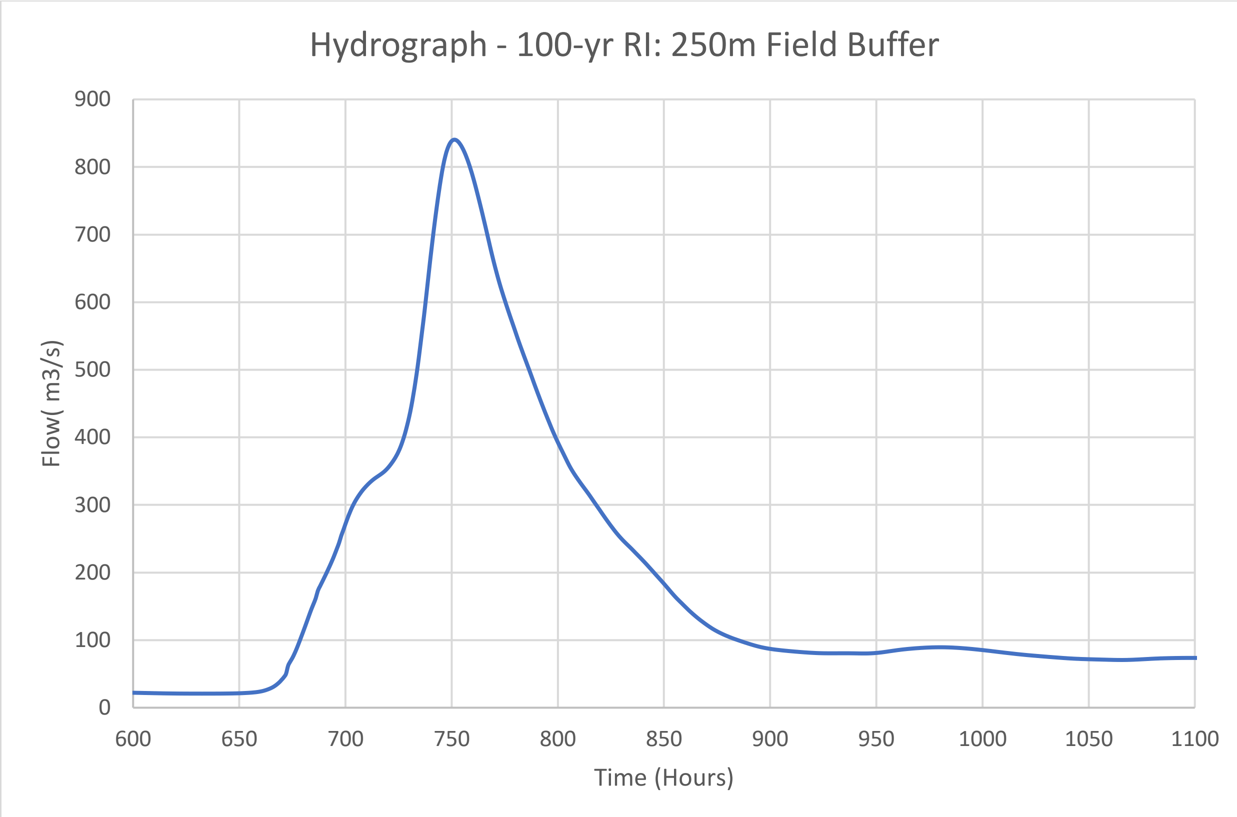
Hydrograph - 100-yr RI: All Field
900
800
700
600
500
400
300
200
100
0
Flow (m3/s)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

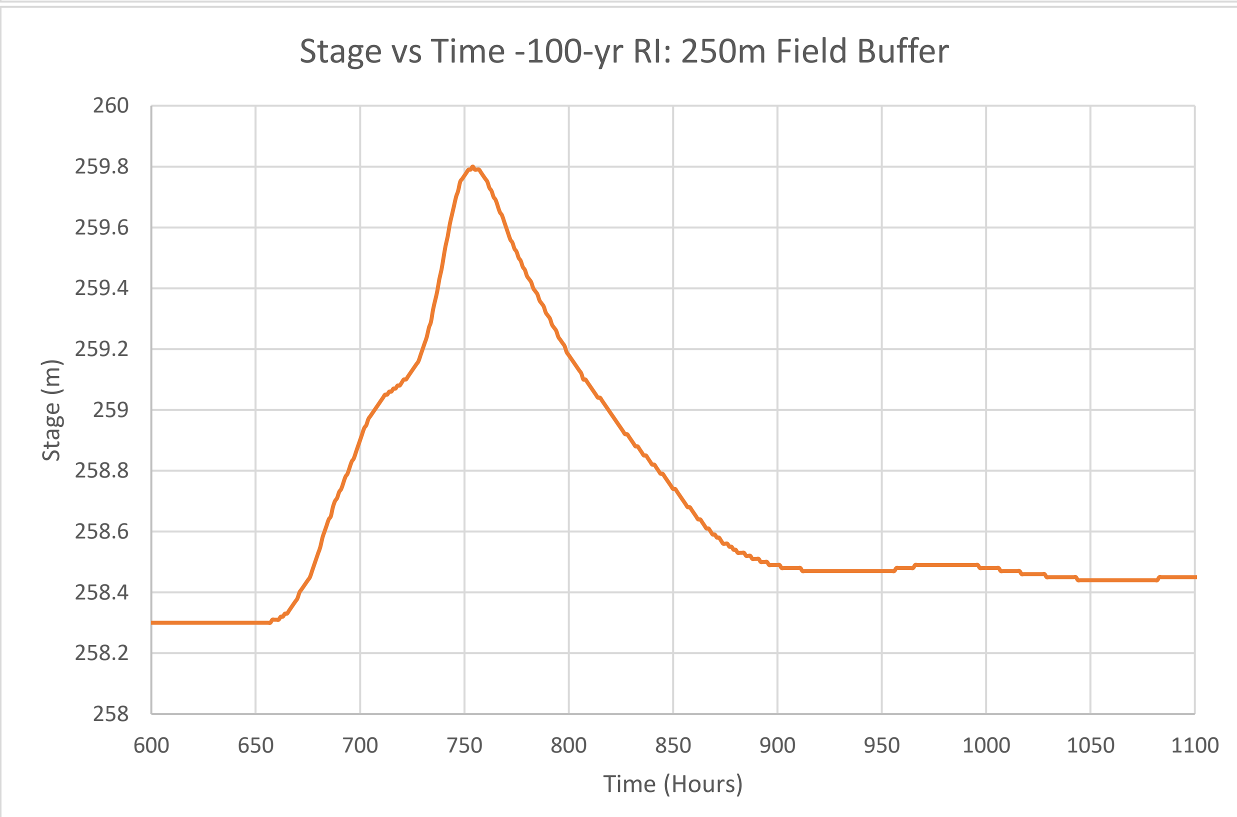


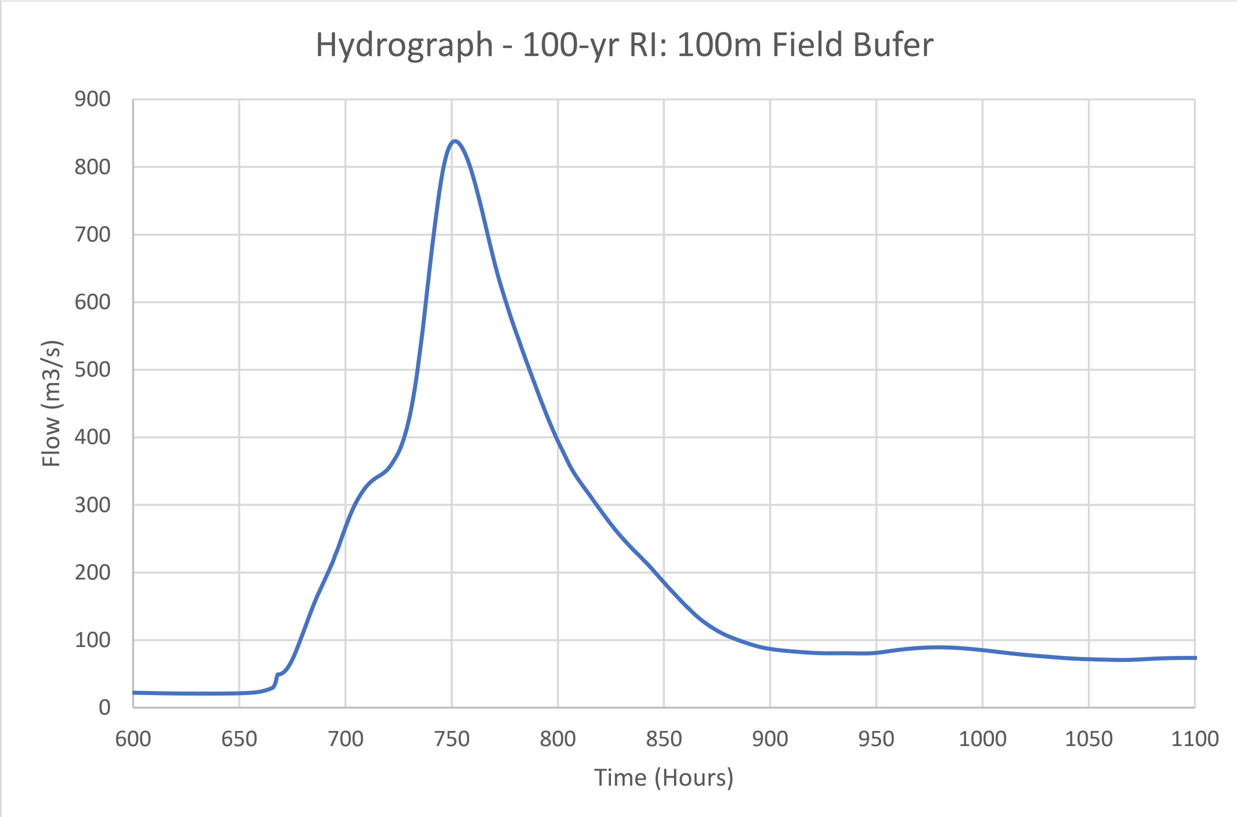
Stage vs Time - 100-yr RI: All Field
259.8
259.6
259.4
259.2
259
258.8
258.6
258.4
258.2
258
Stage (m)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)

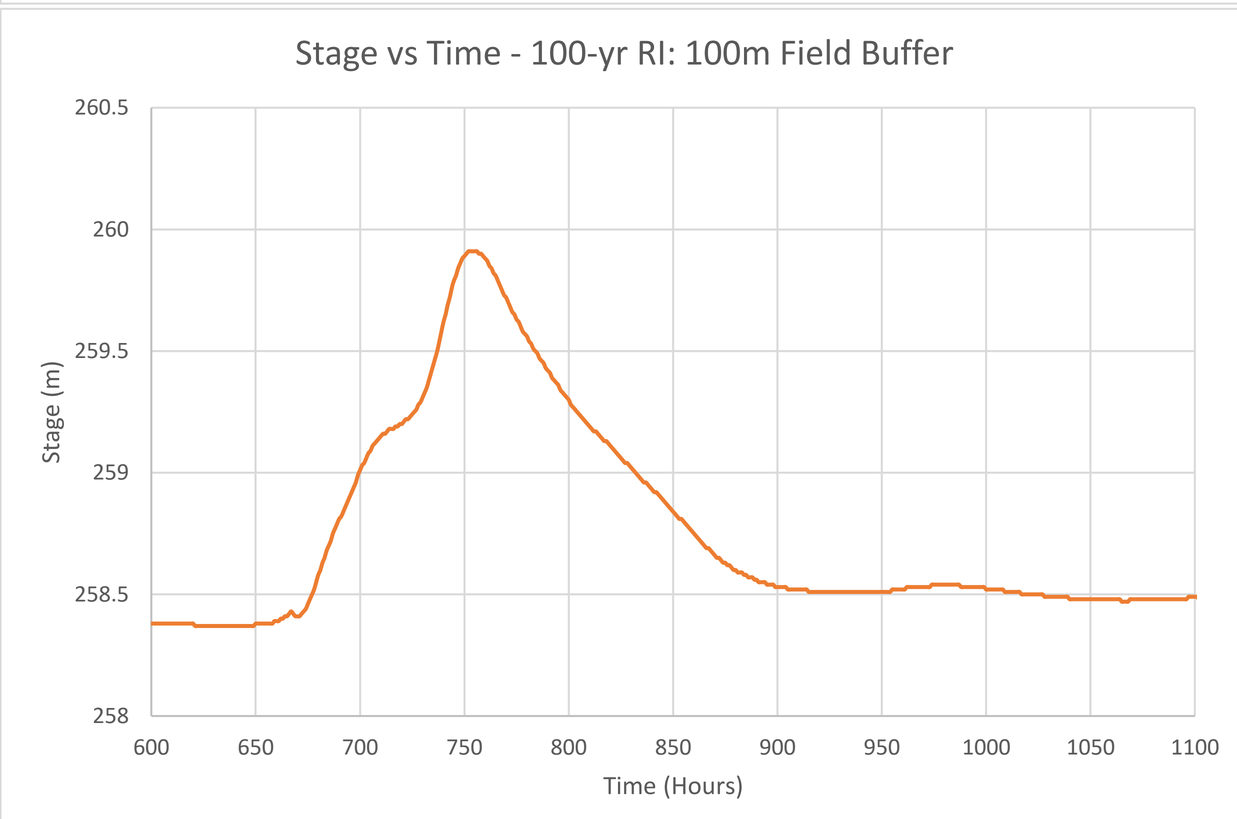

Hydrograph - 100-yr RI: 500m Field
900
800
700
600
500
400
300
200
100
0
Flow (m3/s)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Stage vs Time - 100-yr RI: 500m Field
259.8
259.6
259.4
259.2
259
258.8
258.6
258.4
258.2
258
Stage (m)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Hydrograph - 100-yr RI: 250m Field Buffer
900
800
700
600
500
400
300
200
100
0
Flow(m3/s)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Stage vs Time -100-yr RI: 250m Field Buffer
260
259.8
259.6
259.4
259.2
259
258.8
258.6
258.4
258.2
258
Stage (m)
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Hydrograph - 100-yr RI: 100m Field Bufer
Flow (m3/s)
0
100
200
300
400
500
600
700
800
900
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)


Stage vs Time - 100-yr RI: 100m Field Buffer
Stage (m)
258
258.5
259
259.5
260
260.5
600
650
700
750
800
850
900
950
1000
1050
1100
Time (Hours)